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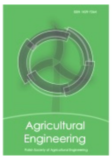

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IDENTIFICATION OF EXTRUSION PROCESS PARAMETERS BASED ON ITS RESPONSE TO THE STEP FUNCTION

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ABSTRACT

The paper presents results of the research on the single-screw extruder strength on sudden changes of dosing raw material during the extrusion process. The tests were carried out in a short single-screw extruder KZM-2 whose relation of length to diameter of a screw was 6:1 and rotational speed was 200 rpm. Grits moistened up to 15% moisture and five disturbing samples of mass 0.2-1.2 kg prepared from the same raw material constituted a research material. Particular samples were used for disturbing a stable course of the extrusion process. Disturbance of the process consisted in fast introduction of the whole disturbing dose to the extruder input and measurement of the value of intensity change of current consumed by the extruder engine, time of return to stable conditions and changes in the image of obtained samples of extruder. Measurements of the impact of disturbance on the measured amounts were carried out for three settings of extruder performance. It was found out that a single-screw extruder at all set performances reacted with fast increase of electric current consumption; moreover, time of process stabilization changed each time. Moreover, it was reported that particular disturbing doses affected significantly the changes of quality parameters of extrudates.

Introduction

Extrusion is a food production technology, which may be presently recognized as a standard method of production of many cereal products e.g. breakfast products, small breads, snacks, pasta or even highly processed meat analogues of plant protein (Wianecki, 1999; Pęksa, 2007; Mitrus, 2010; Wójtowicz, 2011). Possibility of creating the raw material composition, specific for this technology, enables such great diversity. Majority of extrudated products, known on the market, is thus mainly produced of mixtures of few raw materials, which additionally are enriched with such additives as: dyes, seasonings, fats, starches, which are directly applied into the extruder's chamber during the process (Mościcki et al., 2007). Appropriate setting of initial parameters of the process and proper control of an extruder enable formation of the wide array of various products during even one stabilized process (Mościcki, 2002). Undoubtedly, it is an advantage of the extrusion process, however, maintaining a stable course of the process, frequently proves then to be difficult and usually is related to the change of energy consumption of the process, considerable losses of raw material and may also even lead to blocking of an extruder (Ekielski et al., 2007; Wójtowicz and Mościcki, 2008). The reason for destabilization of the process may be a sudden change of a dose, moisture, degree of raw material crushing or the operator's fault, etc. Present systems which control the extruder's operation include a wide range of disturbances (Hamrol, 2005) which result from the character of work of a given type of an extruder through the use of modern systems and algorithms of control e.g. a diffuse control (Erikainen and Linko, 1987; Ekielski, 2006). However, one should emphasise that border conditions in which a specific device may work and the time of the process stabilization after its disturbance are described in literature rather scarcely. Thus, it seems purposeful to recognize the possibility of getting out the extruder from transient state.

The objective and the scope of research

The objective of this work was to identify resistance of the single-screw extruder on sudden changes of dosing raw material during the extrusion process.

The scope of work covered:

1. Carrying out the process of extrusion at variable provision of raw material.
2. Purposeful disruption of the stabilized extrusion process.
3. Assessment of the quality of extrudates obtained during the research.

Methodology of research

The research material consisted in grits purchased in Silesian Grain Sp. z o.o. of moisture 13.1%, starch content 70% and granulation 0.25-0.75 mm. Initial preparation of raw material for extrusion consisted in previous moistening of grits with water to moisture of 15% and mixing it in a continuous mixing machine. Then, a raw material was set aside for approx. 1 hour. Then, four samples of the following mass were weighed out: 0.2 kg, 0.5 kg, 0.8 kg and 1.2 kg. Samples prepared in such a manner as doses which disturb the process, were added directly to the extruder's dose during a stabilized extruder's operation. On account of a constant transport ability of the extruder's screw for the researched material, introduction of a disturbing dose may be treated as introduction of step disturbance of variable duration of operation depending on the present load of an extruder. Thus, function (1) may describe the duration of step disturbance:

$$t = f(Q_i, Q_e) \tag{1}$$

where:

Q_i – is a mass of a disturbing dose (kg),
Q_e – extruder's load (kg·hour^{-1}).

A single-screw extruder KZM-2 of motive power of an electric engine 22 kW in length L to diameter D ratio which is L/D – 6:1 and rotational speed of a screw 200 rpm. The applied extruder's matrix was equipped with two round exhaust nozzles of 6 mm diameter each.

Temperature of the extrusion process measured in the plastification section of an extruder was approx. 130ºC. During the research, an extruder worked in three sets of the speed of the raw material feeder, which corresponded to three various performances of an extruder.

At the setting of the feeder performance:

1. in the 1st position - performance of the process was 80 ($kg \cdot h^{-1}$),
2. in the 2nd position - performance of the process was 110 ($kg \cdot h^{-1}$),
3. in the 3rd position - performance of the process was 160 ($kg \cdot h^{-1}$).

During the process of extrusion, current intensity consumed by the engine of the extruder (A) was registered every second. LabView 7.1. software was applied for data acquisition. A current clamp Z202A by METRAWAT was used for measurement. It was connected to the set for data acquisition by National Instrument, composed of: measurement card - PCI-6024E, module NI SCXI-100 and NI SCXI-1302.

For determination of basic quality parameters of the obtained extrudated products, the following were used: index of radial and volumetric expansion, index of water absorption WAI and water solubility index WSI.

Density of an extrudate was calculated by division of the extrudate mass by its volume. A cylinder with a measure and rapeseeds were used for measurement. Previously weighed amount of extrudate was poured into a cylinder and then precisely mixed with prepared 250 cm^3 of rapeseed. From the read out result previously set value of rapeseed was deducted and volume of the tested extrudate was obtained, from which density in $g \cdot cm^{-3}$ was determined.

Index of volumetric and radial expansion (2,3) was determined with Alvarez-Martinez et al. (1988):

$$SEI = \frac{S_e}{S_d} \tag{2}$$

$$VEI = \frac{\rho_m}{\rho_e} \frac{(1 - MC_m)}{(1 - MC_e)} \tag{3}$$

where:

SEI – degree of radial expansion (-),
VEI – degree of volumetric expansion (-),
S – diameter (mm),
e – extrudate,
d – nozzle,
m – material,
ρ – density ($g \cdot cm^{-3}$),
MC – raw material moisture (%).

Values of water absorption **WAI** and solubility in water **WSI** indexes were determined according to Anderson/s method (1969) from the following relations (4,5):

$$WAI = \frac{\text{weight of sediment}}{\text{weight of dry solids}} \tag{4}$$

$$WSI\ (\%) = \frac{\text{weight of dissolved solids}}{\text{weight of dry solids}} \cdot 100\,\% \tag{5}$$

Statistical analysis

Statistica 10 software was used for statistical analysis. In order to plan an experiment Central Composition Plan (CPK) was generated 2**(2), of 2 input numbers, 2 blocks and 10 systems with iteration, which will later serve for obtaining the area of response. Particular levels of variables were coded to numerical values as values: -1,0,1.

For statistical analysis of the selected parameters additional Taguchi method was used, thus an orthogonal table L9 with the number of input sizes 4 and value 3 was generated (Taguchi, 1993; Statsoft; Kiełbas, 2006). Experience allowed determination of ETA average value calculated as a relation of S signal (English signal factors) to noise N (English: noise factors). ANOVA analysis of variance was used for analysis of variables significance.

For statistical asessment of the quality of adjustment of responses area equations, coefficient of determination R^2, $R^2_{popr.}$ and Mean Square Error were used.

Research results

Diagram 1 presents measurement results of the maximum strength of electric current charged by the engine of the extruder and the time, which the extruder needs to stabilize the course of the extrusion process subjected to disturbances. Diagram shows that both strength of current as well as time of stabilization of the extruder increase along with the increase of a disturbing dose at all set performances of the extruder. It was also found out that the consumption of electric current during extrusion increased along with the increase of efficiencies and reached the highest values of 42.92 A at the performance of 160 ($kg{\cdot}h^{-1}$) and a disturbing dose of 0.8 kg. In the same conditions a dose of 1.8 kg caused that a nozzle of the extruder got stuck and ceased the extrusion process. It was also reported that at the performance of the extruder 80 ($kg{\cdot}h^{-1}$) and 110 ($kg{\cdot}h^{-1}$) differences of the changes in the current charge were the highest, but at the performance of 160 ($kg{\cdot}h^{-1}$) differences in the current charge were lower, time of extruder stabilization got longer and it was even as much as 260s. In case of the remaining measurements of times necessary for stabilization of the extrusion process, it was determined that they were within 20s for the lowest disturbing dose at performance of 80 ($kg{\cdot}h^{-1}$) and 125 s at a disturbing dose of 0.5 kg and performance 160 ($kg{\cdot}h^{-1}$).

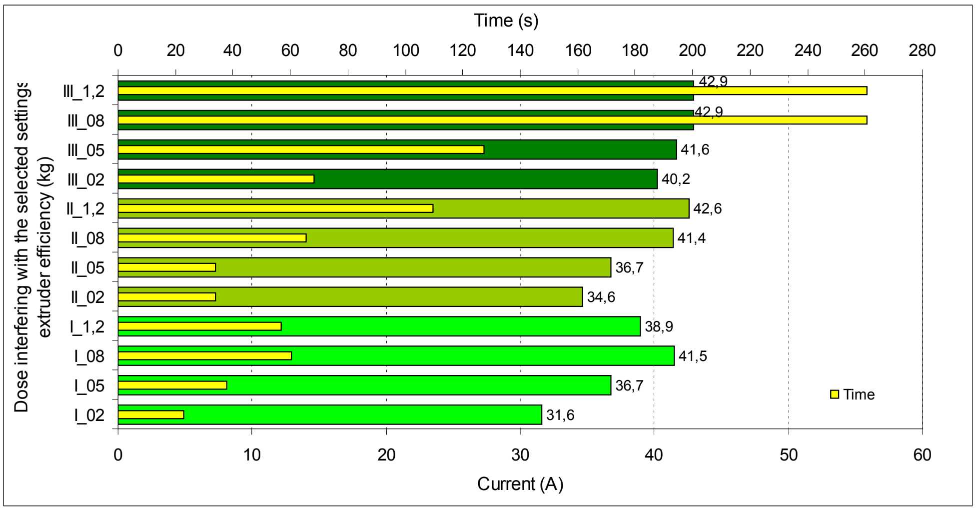

Figure 1. Impact of the amount of a disturbing dose and extruder performance on the changes of current intensity consumed by the extruder engine.

It was found out that the change of proportion of a disturbing dose caused also explicit changes of the index of extrudate expansion, which may be observed even visually. Each time after application of a disturbing dose the obtained extrudate was characterized explicitly by a higher volume.

In order to carefully analyse the assessment of the impact of changes in a disturbing dose on the quality of the obtained extrudates during destabilization of the process of extrusion statistical analysis was carried out by subjecting results of empirical research to ANOVA analysis of variance (table 1). Considering the index of volumetric expansion it was found out that all analysed factors were significant except for the parameter · of extruder performance (the effect of the second row). Similarly in case of the radial expansion index, majority of factors proved to be significant except for the impact of the disturbing dose (the effect of the first row). When analysing WSI index, it was found out that only effects of the second row for a disturbing dose had an insignificant impact. In case of WAI index, it was found out that only change in performance of the extruder was a significant factor.

In further analysis after elimination of insignificant variables from the obtained result coefficients of regression were calculated, from which regression equation was developed and response areas were determined (tab. 2). Omitting insignificant factors resulted in added to the error increasing thus its mean square MSE and contributed to the decrease of probability *p*.

Table 1
Analysis of variance

	Volumetric expansion (–)				
Parameter	SS	df	MS	F	p
(1) Disturbing dose (kg)	75.1825	1	75.1825	70.2352*	0.0000
Disturbing dose ^{2} (kg)	25.3032	1	25.3032	23.6382*	0.0003
(2) Performance of extruder (kg·h^{-1})	75.3793	1	75.3793	70.4192*	0.0000
Performance of extruder ^{2} (kg·h^{-1})	0.1090	1	0.1090	0.1018	0.7544
1 wz. 2	9.8410	1	9.841	9.1934*	0.009
Error	14.9861	14	1.0704		
	Radial expansion (–)				
(1) Disturbing dose (kg)	0.1324	1	0.1324	1.0424	0.3246
Disturbing dose ^{2} (kg)	1.7081	1	1.7081	13.4481*	0.0025
(2) Performance of extruder (kg·h^{-1})	1.9644	1	1.9644	15.4664*	0.0015
Performance of extruder ^{2} (kg·h^{-1})	6.7511	1	6.7515	53.1534*	0.0000
1 wz. 2	0.7328	1	0.7328	5.7696*	0.0308
Error	1.7782	14	0.1270		
	WSI (%)				
(1) Disturbing dose (kg)	259.0240	1	259.0240	40.6377*	0.0000
Disturbing dose ^{2} (kg)	16.6230	1	16.6230	2.6079	0.1286
(2) Performance of extruder (kg·h^{-1})	1256.507	1	1256.5070	197.1302*	0.0000
Performance of extruder ^{2} (kg·h^{-1})	95.2250	1	95.2250	14.9396*	0.0017
1 wz. 2	31.7030	1	31.7030	4.9739*	0.0426
Error	89.2360	14	6.3740		
	WAI (–)				
(1) Disturbing dose (kg)	0.2133	1	0.2133	3.0039	0.1050
Disturbing dose ^{2} (kg)	0.0001	1	0.0001	0.0008	0.9780
(2) Performance of extruder (kg·h^{-1})	3.6633	1	3.6633	51.5806*	0.0000
Performance of extruder ^{2} (kg·h^{-1})	0.0516	1	0.0516	0.7267	0.4083
1 wz. 2	0.0875	1	0.0875	1.2327	0.2855
Error	0.9943	14	0.0710		

* Significant difference at the level of significance $p \leq 0.05$

Table 2

Regression equations of the area of response and values of the coefficient of determination and the mean square error MSE

$R^2 = 0.921$ $R^2_{popr} = 0.901$ MSE = 1.0063

$$EO = -262 + 28.47 \cdot x - 10.24 \cdot x^2 + 0.102 \cdot y - 0.091 \cdot x \cdot y$$

$R^2 = 0.8578$ $R^2_{popr} = 0.8199$ MSE = 0.1274

$$ER = 11.297 + 20.918 \cdot x - 0.115 \cdot x^2 + 0.0005 \cdot y - 0.007 \cdot x \cdot y$$

$R^2 = 0.\ 9229$ $R^2_{popr} = 0.\ 9085$ MSE = 8.3950

$$WSI = 27.576 + 12.584 \cdot x - 0.337 \cdot y + 0.003 \cdot y^2$$

$R^2 = 0.7314$ $R^2_{popr} = 0.7165$ MSE = 8.3950

$$WAI = 5.928 - 0.013 \cdot y$$

Diagram (fig. 2) presents changes of the volumetric expansion index as the function of performance and a disturbing dose of the extruder. Diagram shows that the values presenting the volumetric expansion index increased along with introduction of the increased disturbing dose at all performances of the extruder. At performance of 80 ($kg \cdot h^{-1}$), values of this index reached the lowest values but at setting the performance of 160 ($kg \cdot h^{-1}$) the highest. One may notice a slow inclination of the surface downwards on the diagram, which suggests that a dose of raw material 1,2 in the conditions of the highest performance of the extruder may cause sudden decrease of the degree of expansion resulting for example from the local increase of temperature and blocking of the nozzle of the extruder. In case of the index of radial expansion (fig. 3) it was determined that the change of the extruders performance clearly affected changes of the extruder's performance. Despite determined small increase of the parameter along with the change of a disturbing dose, differences between particular samples were slight.

When analysing the course of diagram (fig. 4) one should pay attention that values of solubility index for extrudate in water, change both along with changes of disturbing doses as well as with changes of setting a feeder of the extruder . Linear course of diagram and high value of coefficient of determination $R^2=0.94$ may suggest very clear changes of this index and good adjustment of empirical data to calculated area of response. The highest values of WSI index achieved at setting the performance at the level of 160 ($kg \cdot h^{-1}$) and simultaneusly very low values of WAI index (fig. 5) particularly in case of destabilising doses of raw material 0.8 kg and 1.2 kg indicated highly progressed starch degradation in extrudates produced in these conditions. In case of extrudates it may not be a desirable feature and such products the most probably may have unsatisfactory sensory values e.g. perceptible taste of burning as a result of local change of temperature of raw material. High values of WSI may also affect reduction of density and the volumetric expansion index (Ekielski et al., 2007).

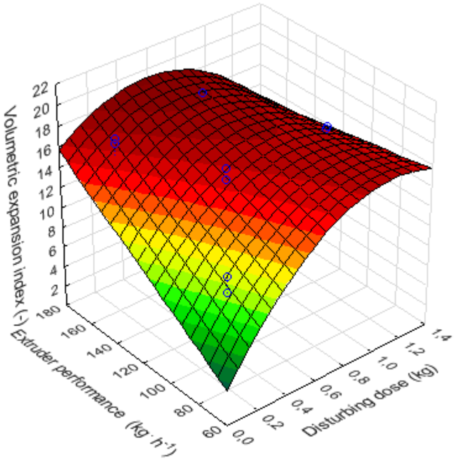

Figure 2. Impact of a disturbing dose and the extruder performance and on the volumetric expansion index

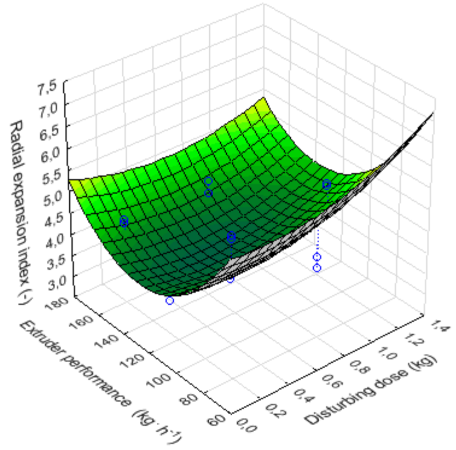

Figure 3. Impact of a disturbing dose and the extruder performance and on the radial expansion index

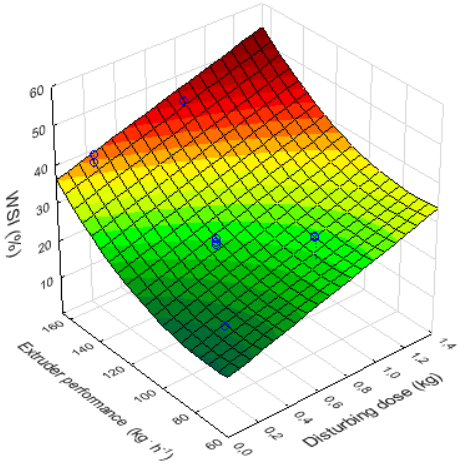

Figure 4. Impact of the disturbing dose and extruder performance on WSI index

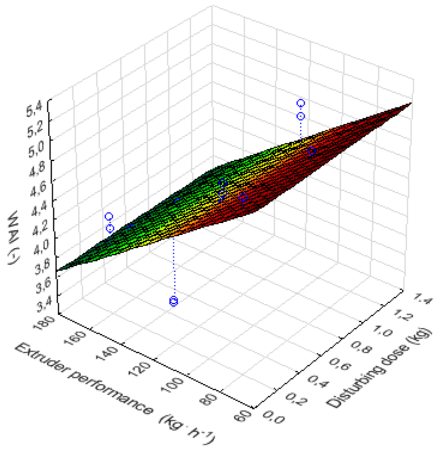

Figure 5. Impact of the disturbing dose and extruder performance on WAI index

Volumetric expansion index and WSI, significance of which was confirmed in the analysis of variance ANOVA was additionally analysed with the use of experience with Taguchi method.

As additional variables in Taguchi orthogonal table, the maximum values of temperature changes and raw material moisture were applied, which slightly changed as a result of applied doses, that disturb the process of extrusion or minimum regulation of water additive in order to maintain continuity of the extrusion process.

The objective of this analysis was to minimize the product variability as a response to *disturbing* factors that is *noise* (N) at simultaneous maximization of variability in response to factors of *signal* (S). The result of the analysis was obtaining average value of coefficient S/N Eta towards input sizes followed from the analysis which was carried out. In the experiment, which analyses the impact of disturbing doses on the value of volumetric expansion index and water solubility index WSI a type of the research problem in the Taguchi method know as: "nominal – the best" where values of dependent variables (y) are higher or equal to), were used. Ideal values > 0. Below a formula (6) for calculation of the constant value of signal was presented (nominal values), where variability around this value may be treated as a result of noise operation:

$$ETA = 10 \cdot \log 10\left(\frac{m^2}{s^2}\right) \tag{6}$$

where:

m – mean,
s^2 – variance.

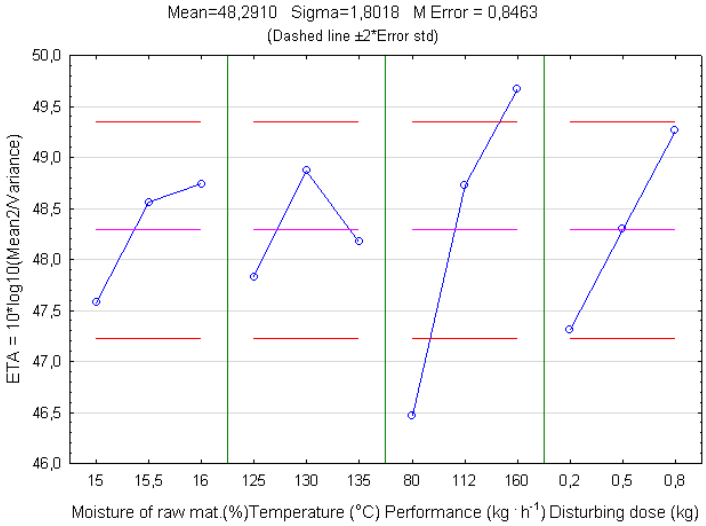

Figure 6. Diagram of average values of ETA (coefficient S/N) of the volumetric expansion index towards values of the analysed factors

On diagram (fig. 6) where mean values of ETA (index S/N) towards the value of analysed factors for volumetric expansion index, settings of each input value may be recognized, which means settings maximizing the value of coefficient S/N to which changes of extruder performance are included and a disturbing dose, were presented. The remaining variables of raw material moisture and temperature were fluctuating around the mean value of ETA and did not significantly influence the course of experiment.

Diagram (fig. 3) which presents mean ETA values of WSI index one may observe that the border of double standard deviation was exceeded by temperature within (130-135ºC) and performance (160 kg·h^{-1}).

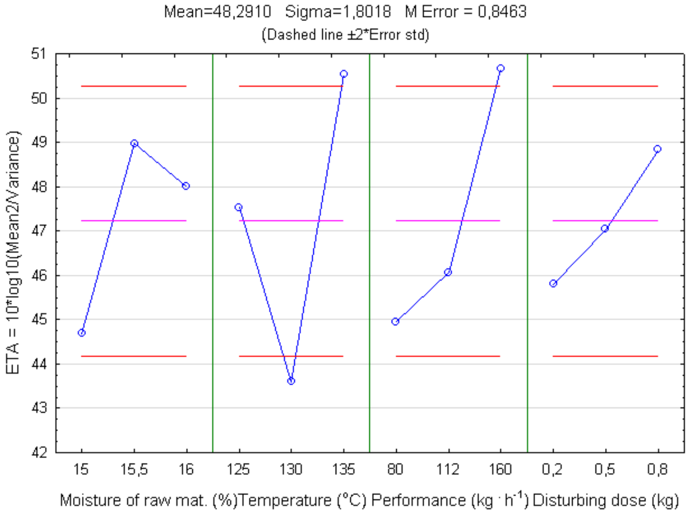

Figure 7. Diagram of mean values of ETA (coefficient S/N) towards values of the analysed factors

Observed explicit impact of the process temperature operation, which, despite the fact that it was determined in a constant scope, could follow from a short-term local increase as a result of sudden changes in the raw material dose. In short time on account of high temperature inertia of the extruder, such changes could not be recorded by the measurement system. In case of the remaining parameters i.e. a disturbing dose and moisture of raw material were around average value of ETA and their variability was low.

Conclusions

1. Measurements of the strength of electric current during disturbance of the extruder's operation proved that the consumption of energy clearly increased as a result of disturbance of the extruder's operation. It was found out that differences between the values were the highest in case of the set lowest performance of the extruder and the lowest in

case of the highest performance. Such behaviour may be a positive feature of single-screw extruders because the excess of raw material in conditions of the highest load of the extruder is withdrawn from the section of plastification in the back flow not causing each time the extruder's lock.

2. Disturbance of operation of the analysed extruder resulted in the explicit change of the quality of extrudated products. However, it should be emphasised that the quality of products was satisfactory in case of the dose 0.2; 0.5 and 0.8 kg and explicit deterioration of the quality was noticeable at the disturbing dose the highest of which was equal to 1.2 kg irrespective of the set performance of the extruder.
3. High values of WSI index achieved at the highest performance of the extruder may follow from the high sensitivity of the extrusion process to the changes in the temperature of the process even within the scope up to 5°C.

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IDENTYFIKACJA PARAMETRÓW PROCESU EKSTRUZJI NA PODSTAWIE JEGO ODPOWIEDZI NA WYMUSZENIE SKOKOWE

Streszczenie. W pracy przedstawiono wyniki badań odporności ekstrudera jednoślimakowego na nagłe zmiany dawki podawania surowca w trakcie procesu ekstruzji. Badania przeprowadzono w krótkim ekstruderze jednoślimakowym KZM-2 o stosunku długości do średnicy ślimaka 6:1 i prędkości obrotowej 200 obr·min^{-1} (rpm). Materiałem badawczym była kaszka kukurydziana nawilżana do wilgotności 15% oraz pięć próbek zakłócających o masie 0,2-1,2 kg przygotowanych z tego samego surowca. Poszczególne próbki posłużyły do zakłócenia ustabilizowanego przebiegu procesu ekstruzji. Zakłócenie procesu polegało na szybkim wprowadzeniu do wejścia ekstrudera całej dawki zakłócającej i pomiarach wartości zmiany natężenia prądu pobieranego przez silnik ekstrudera, czasu powrotu do warunków stabilnych oraz zmian w obrazie otrzymanych próbek ekstrudatu. Pomiary wpływu zakłócenia na mierzone wielkości przeprowadzano dla trzech ustawień wydajności ekstrudera. Stwierdzono, że ekstruder jednoślimakowy przy wszystkich ustawionych wydajności reagował szybkim zwiększeniem poboru prądu elektrycznego, każdorazowo zmieniał się także czas ustabilizowania procesu. Zaobserwowano również, że poszczególne dawki zakłócające wpływały istotnie na zmiany parametrów jakościowych ekstrudatów.

Słowa kluczowe: ekstruzja, ekstruder, ekspansja, Taguchi, zakłócenia