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Effect of selected parameters of double-screw extruder operation on fractal dimensions of the extrudate

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Abstract: *Effect of selected parameters of double--screw extruder operation on fractal dimensions of the extrudate.* There are presented problems of changes in the length and fractal area of the wheat-maize extrudate cross sections, depending on moisture content of supplied material and rotational speed of extruder's screws.

Key words: extrusion, fractal dimension, moisture content, double-screw extruder.

Notation
DF – fractal dimension [–],
FD_p – fractal dimension of area [–],
DF_{SC} – fractal dimension of pore wall length [–],
n – rotational speed of extruder screw [rpm],
w – material moisture content [%],
L – length of extruder screw,
D – diameter of extruder barrel.

INTRODUCTION

The porous structure of starch product extrudate determines its physical and textural properties; it results from a rapid change in aggregation state of water contained in the starch subjected to processing. Occurrence of different empty spaces inside the extruded starch products is connected with the process of transformation of semi-cristalline amylose and amylopectin chains into an amorphous form [Brent et al. 1997], that allow for building the empty special structures. Therefore, the structure and configuration of pores can be the basis for complex evaluation of qualitative transformations of starch occurring during extrusion and affect the textural properties of extrudates [Peleg 1997]. Description of extrudate internal structure calls for introduction of magnitudes describing the mean size of pores, their number on cross-section unit, geometric orientation of pores [Yuilani et al. 2006] or the wall thickness between pores of extrudate. Some generalization of previously described magnitudes is extrudate porosity measurement [Cisneros and Kokini 2002], that described in general the share of empty spaces in extrudate sample.

Modelling of sensory properties of the obtained extrudate, depending on its internal structure described with the mentioned parameters, generally led to development of functional models of law flexibility [Alavi et al. 2003; Alvarez-Martinez 1988]. It resulted from the nature of magnitudes introduced to description spaces of regular shapes [Chang 1992]. The sensory magnitudes: crispness and hardness are significantly related to extrudate internal structure [Ekielski 2005]. Therefore, the lack of full description calls for searching of more flexible indices describing the details of extruded products' structure.

An interesting parameter enabling to obtain more information on internal structure of expanded extrudate is fractal dimension (FD), that allows for description of the extrudate structure complexity. The fractal dimension is a good estimator for structure complexity of the systems of irregular and not systematized shapes [Mandelbrot 1983].

Among many fractal properties some can be regarded as fundamental. The basic feature of fractals is their self- similarity; it means the lack of change in appearance (e.g. image) along with the change in magnification scale in which a given magnitude is observed. In the case of synthetic fractals this should be taken literally. The fractals existing in nature fulfill this assumption very rarely, therefore, one can here speak about approximation to fractal structure. The second condition is infinite complexity of the fractal, consisted in occurrence of fractal structures with an increase in observation accuracy. In the case of real fractals the fulfillment of this condition is difficult due to limitations in the measuring equipment. In the field of equipment's measuring range the occurrence of structure-generating phenomenon with the change in scale accuracy enables to assume continuity of this phenomenon and discrimination of elements characterized by fractal structures [Mandelbrot 1983]. The condition sufficient for existing the fractal structure is fulfillment of statistical self-similarity equation.

The image analysis and calculations of fractal dimensions were carried out with the use of well known box algorithm [Leibovitch and Toth 1989].

The fractal dimension is presented with the equation (1):

$$DF = lim_{r \to 0} \left(\frac{\ln(\mathrm{N})}{\ln\left(\frac{1}{r}\right)} \right) \quad (1)$$

where: N – number of objects of dimension r visible in analyzed area. If in measurement domain of graduation changes r there is a linear dependence ln N = ln (1/r), the occurrence of fractal dimension for a given form can be admitted [Leibovitch and Toth 1989].

The complex internal structure of extrudate can be described with the fractal dimension, if necessary conditions confirming its fractal structure are fulfilled.

Changes in the fractal dimension may point out at development of extrudate's internal structure. The morphological changes lead to changes in sensory properties of the obtained extrudate. This work aims at presentation of changes in calculated fractal dimension of the area and edges of pore walls depending on variable control parameters of extrusion process.

MATERIAL AND METHODS

In investigations there was used a single-screw extruder of concurrent direction of screw rotation and ratio L/D = 20. Rotational speed of extruder screws amounted to n €{140, 190, 240} rpm. The extruder was equipped with four heating sections of set temperature: 140, 120, 80, 70°C (from the die). The temperature was maintained by a two-stage control system controlled with PLC controller. Material flow rate supplied to the screw amounted to 100 kg/h. The extruder die consisted of 4 round holes of diameter 5 mm each.

There was investigated the extrudate produced of wheat and maize flour of full grain milling. The raw material was purchased on the local market. The initial moisture content of flour was equal to 10%. The samples were prepared by weighing the dry components. The share of wheat flour amounted to 70%, the share of maize flour 30%; the total dry component mass was equal to 50 kg. The measured out components were put into an arm mixer; water was added during mixing. Each investigated mixture was mixed for 10 minutes in a chamber vane mixer of mixing element's rotational speed 5 rev/sec. The raw material composition of the mixtures is presented in Table 1.

Each recipe was prepared in three replications, while the obtained extrudate was collected for every experiment. Each sample contained about 50 granules; 5 of them were selected for further investigations.

IMAGE ANALYSIS

The cross-section of sample was executed along the longest edge. The obtained cross-section samples were placed under the optical microscope equipped with CCD camera of resolution 5Mpix; the photographs were made at magnification ×5 and recorded in bmp format. The image analysis was performed with the use of program Matlab v.7.7, application Fraclab. The obtained multicolour images were transformed into monochromatic ones of 8-bit grayness scale. Investigations on fractal dimension of internal walls of extrudate called for discrimination of insignificant image fragments; it was performed with the use of Sobel's differential filter algorithm, transformed into a bit-map. The fractal dimension FD_{SC} was calculated with the use of a box algorithm for analysis of image obtained from the Sobel's edge filtration. Calculation of pore area fractal dimension called for transformation of analogue image into the two-stage system (bit-map) and again for application of box algorithm to calculate the area fractal dimension.

To draw the response surface diagrams the experiment planning module DOE of Statistica program was used.

TABLE 1. Composition of investigated mixtures

Recipe	Raw material composition [kg]			Overall moisture content of mixture [%]
	Wheat flour	Maize flour	Water	
A1	35	15	2.5	14.3
A2	35	15	5	18.8
A3	35	15	10	25.0

RESULTS OF INVESTIGATIONS AND DISCUSSION

Fractal dimension of extrudate walls and area

Fulfillment of condition sufficient for existence of fractal structure of investigated extrudates: the subsequent image transformations and the course of fractal structure graduation function for the selected sample are presented in Figure 1. All carried out measurements showed a linear nature of changes in the measured magnitudes as a function of changes in observation resolution (Fig. 1e).

The average results of measurements on pore wall fractal length FD_{SC} are presented in Table 2.

The average values of fractal dimension of pore area are presented in Table 3.

The response surface diagrams FD_p and FD_{SC} are presented on Figures 2a and 2b. The highest values of area fractal dimension FD_p for investigated extrudates were found at low moisture content of raw material and at high rotational speed of the screws. The least values of these indices were found at low rotational speed of he screw and moisture content from 20 to 24%. Further increase in moisture content caused an increase in FD_p values. The high values of area fractal dimension point out at substantial variation of the investigated areas of pores and their irregular distribution in-

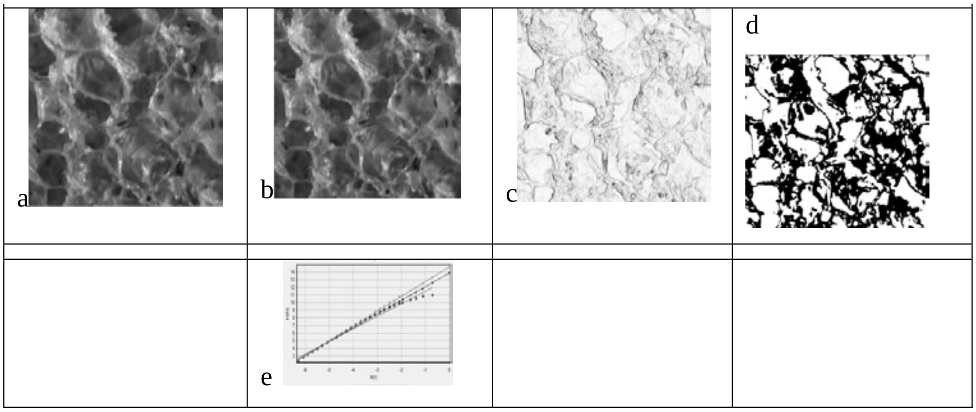

FIGURE 1. Exemplary image of extrudate after subsequent transformations: a – original view, b – transformation into monochromatic form, c – edges of walls, d – bit-map with marked pore areas, e – approximation of curve describing fractal dimension of sample edge length, r^2 = 0.997

TABLE 2. Fractal dimension of pore walls FD_{SC} of extrudate depending on moisture content and extruder's screw rotational speed

Raw material moisture content w [%]	Rotational speed of screw n [rpm]		
	140	190	240
14.3	1.45	1.52	1.61
18.8	1.55	1.45	1.44
25.0	1.22	1.25	1.43

TABLE 3. Fractal dimension of pore area FD_p of extrudate depending on moisture content and extruder's screw rotational speed

Raw material moisture content w [%]	Rotational speed of screw n [rpm]		
	140	190	240
14.3	2.54	2.72	2.86
18.8	2.52	2.57	2.60
25.0	2.1	2.33	2.51

a b

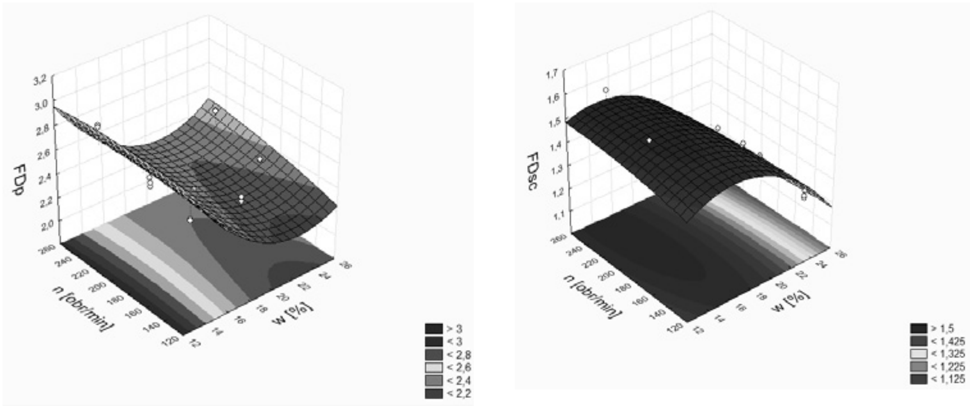

FIGURE 2. Changes in fractal dimension depending on rotational speed f screws and moisture content of sample: a – dependence $FD_p = f(n, w)$, b – dependence $FD_{SC} = f(n, w)$

side the extrudate cross-section. The low values of FD_p point out at small variation of pore areas, however, it should not be unequivocally connect with their small dimensions. At low moisture content the product exspansion proceeds very rapidly and dynamically. It often results in different internal structure of extrudates due to limited heat transfer to particular material particles that causes the local overheating of material. This can lead to creation of considerable empty spaces inside the obtained product that is usually badly received by the consumers [Ekielski et al. 2007]. The high moisture content of raw material from one side causes a good heat transfer in the material, but during pushing up of material off the die, large amount of quickly evaporating water results in quick cooling of material. This phenomenon (described in references) causes creation of few pores of various shape and area inside the extrudate. The course of changes in FD_{SC} parameter was opposite to previously described course of FD_p. It should be noted that the extreme values of these parameters are not situated in the same areas. This points out at weak dependence between these parameters or even the lack of it. The fractal dimension of internal wall length of the extrudate describes variation of its shape; the higher value means its more jagged shape and substantial differences between the cells. The effect of rotational speed of extruder's screws on the index describing complexity of extrudate wall structure was small, due to good mixing features of concurrent double-screw extruders and proper configuration of the extruder's screws. It should be noted that in the contrary to FD_p index, at moisture content below 14% the FD_{sc} value begins to decrease. It means that despite the variation in the pore sizes their edges become less jagged. One can assume that it is caused by the maximal stretching of starch structures during expansion process. The highest values of FD_{sc} were found at moisture content 16–18%, which points out at substantial development of the pore walls. This is a very interesting area with fairly uniform empty spaces, but with walls of different structure. An increase in moisture content of the mixture causes a decrease in FD_{SC} dimension, resulted from uniform lines of pore edges. Similarly to FFD_p it can be caused by a decrease in viscosity of the material leaving the die and resulted from a high moisture content of ready extrudate.

CONCLUSIONS

The analysis of changes in the length and fractal area of extrudate cells showed that they are a significant supplement of investigations on the obtained structure. The fractal dimensions will be useful in all cases of accidental changes in the measured values. In the carried out investigations there was proved the existence of fractal structures in cereal extrudates. At the same time, the discrepancy between the fractal area dimension and the fractal length was found. The analysis of fractal spectrum is a valuable tool enabling to predict the obtained product properties.

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Streszczenie: *Wpływ wybranych parametrów pracy ekstrudera dwuśrubowego na wymiary fraktalne otrzymanego ekstrudatu.* W pracy przedstawiono wyniki badań wpływu wilgotności i prędkości obrotowej śrub w ekstruderze dwuślimakowym na fraktalną długość krawędzi występujących w porowatej strukturze ekstrudatów oraz na fraktalną powierzchnię por ekstrudatu. Jako materiał badawczy zastosowano mieszankę pszennokukurydzianą o wilgotności początkowej 10%. Mieszankę nawilżano poprzez dodanie w trakcie jej mieszania: 2,5, 5 i 10 kg wody. Badania przeprowadzono przy trzech prędkościach śrub ekstrudera: 140, 190, 240 obr./min. Wyniki badań wykazały istotny wpływ wilgotności na obliczane wymiary fraktalne uzyskanego ekstrudatu. W czasie badań stwierdzono brak istnienia istotnego wpływu fraktalnej długości krawędzi por na fraktalny wymiar powierzchni por.

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