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Editors : Jorge C. Oliveira, Leon G.M. Gorris
Project Coordinator : Fernanda A. R. Oliveira
Area leader : Leon G.M. Gorris

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Determination of the Stream Flow Structure of Wheat Semolina During Extrusion with a Single Screw Extruder

At. Lambrev, M. Angelov, Y. Chalamov and Y. Lambrev

Higher Institute of Food and Flavour Industries, 26 Maritza blvd
4002 Plovdiv, Bulgaria

Abstract

During extrusion cooking of non-Newtonian products obtained from grain raw materials, the viscosity of the material melted inside the machine depends not only on the temperature and the velocity gradient but also on the residence time and on the intensity of the mechanical force. The movement of the product in a single screw extruder is not uniform because it is a result of three streams, which contributes to the fact that different particles of a given product have different residence times inside the extruder. The retention time of the product can be considered as a continuous variable, changing in a defined interval according to a given statistical distribution. The main purpose of this study was to find the type of the curves of the residence time distribution (RTD) during wheat semolina extrusion and on the basis of the evaluated statistical parameters of these distributions determine the type of stream structure in a single screw cooking extruder with a long screw. To achieve the main purpose of the study a fractional factorial experimental design of type 2^{5-2}, was used.The distribution of the product residence time was measured with a spectrophotometer type "Pye Unicam Pu 8000". Four regression models were evaluated, relating the minimum average residence time of wheat semolina in the machine, the **Pe** number, the number of the conventional cells in which the screw reactor is divided, the rotational frequency of the dosing and pressing screw, the temperatures of the second barrel zone and the matrix and moisture of the processed semolina. It was found that the lowest values of the **Pe** number were obtained at higher matrix temperatures or high moisture and low rotational speed of the processing screw. By using the **Pe** number and the number of cells in which the screw reactor is divided, a single screw extruder with ratio **L/D=20** was classified as *"ideal"* mixer.

1. Introduction

The important factor that influences the structural-mechanical properties of hot-extruded materials is the duration of the technological process (the residence time - RT - of the material in the extruder). It is known that for non-Newtonian products the viscosity of the melted material depends not only on the temperature and on the velocity gradient, but also on the duration and intensity of the mechanical action. That is why Bruin *et al,* (1978) have developed research methods to determine the residence time. Their results consider the die effect and moisture content and they concluded that soy products flow faster than wheat products during extrusion.

Smith *et al*, (1980) investigated the duration of the process on the destruction of bacteria. In the experiments, soy and wheat semolina were used, with their moisture ranging between 18% and 30%. They found that the velocity of the feeding and the pressing screw and the temperature of the barrel influenced strongly the residence time of the material in the extruder, and that due to longer residence time the structure of the material was being destroyed.

Mosso *et al*, (1982) and Barres *et al,* (1990) studied the influence of the residence time on the rheological properties of the hot-extruded product and found that the RT decreased when they increased the rotational speed of the screw (for a twin-screw extruder) and as a result the production output was increased. They also found that the high speed of the pressing screw is the reason for decreasing the RT, which results in a decrease of the duration of the high-temperature processing of the product and finally in a lower viscosity. Spadaro *et al* (1971) studied the extrusion of rice mixed with cotton seed peanuts and found that increasing the rotational speed of the pressing screw decreased the degree of gelatinisation of starch due to shortening the RT and decreasing the shear stress effect.

After extrusion of a maize and soy blend (60:40) Molina *et al,* (1978) stated that the final moisture of the extrudates is closely connected to the output and the RT of the material in the extruder. It was determined that the viscosity of the material during extrusion depends not only on the velocity gradient and on the temperature, but also on the duration of its residence in the machine (Jao and Chen, 1978).

Anderson *et al.* (1969) had found that during maize semolina extrusion the gelatinization depends on the temperature of the material and on its RT. To determine the minimum RT, a dye is usually used. To determine the average RT, Mosso *et al,* (1982) used the concentration of the dye in the extrudates, the time interval between two samples during extrusion, and the RT of every sample in the extruder.

This short survey shows that the RT of the raw material in a hot extruder is an important technological parameter that influences strongly the viscosity of the melted material, the degree of cooking and mixing and the output. The flow is not uniform, as it is a result of three flows: a forward, a backward and a circulating flow in the space determined by one screw flight. This is why different particles of the product reside for different periods of time in the extruder, and that makes it possible for us to describe the RT as a continuous stochastic (random) variable that changes in a certain range and abides by a statistical frequency distribution.

The main purpose of this project is to determine the type of RT distribution curve in a single screw extruder and then by using its statistical parameters, introduce the abstract concept of an "ideal apparatus" to describe the structure of the flow in a single screw extruder.

2. Materials and Methods

2.1. Preparation of the raw material

In our research we have used wheat semolina with initial moisture content of 13.6% and average size of the particles 240μm. Before extrusion, water was added to the material to acquire the necessary moisture, after which it was mixed for 10-15 min, and than the samples were kept in closed polyethylene bags for 12 hours at 5°C to homogenise the moisture in the entire volume of the samples. Before the experiments began, the bags were opened and kept for 2 hours at room temperature.

2.2. Experimental Design

A fractional factorial design of the 2^{5-2} type with generating relations $X_4=X_1X_2X_3$ and $X_5=X_3X_4$ was used, which makes it possible to determine the influence of 5 (five) independent variables with a comparatively small number of experiments.

The names of the input factors in natural form **Z_j** (independent variables) and their level of variation are shown in table 1.

Table 1
Intervals of variation of the process variables

Independent variables (Input factors)	Basic level $Z_j = 0$	Interval of variation ΔZ_j	Upper level Z_j^u	Lower level Z_j^L
Rotational speed of the pressing screw, Z_1, min^{-1}	200	50	250	150
Rotational speed of the feeding screw, Z_2, min^{-1}	15	5	20	10
Temperature of the second zone of the barrel, Z_3,°C	130	10	140	120
Temperature of the die, Z_4,°C	150	10	160	140
Input moisture of the material, Z_5, %	16	3	19	13

As parameters of optimisation (dependent variables), we have chosen the minimum RT (**t_{min}**, s), the average RT ($\bar{t}$, s), the maximum RT (**t_{max}**, s), the Peclet number (**Pe**) and the number of cells (**m**).

The fractional factorial experimental design matrix is shown in table 2. The experiments were performed in a single-screw extruder "BRABENDER 20 D" with screw compression 4:1, die with 4 mm diameter and temperature of the first zone of the extruder 130°C.

Table 2
Matrix for experiment design

Number of experiment	X_1	X_2	X_3	X_4	X_5	Z_1, min^{-1}	Z_2, min^{-1}	Z_3, °C	Z_4, °C	Z_5, %
1	-1	-1	-1	-1	+1	150	10	120	140	19
2	+1	-1	-1	+1	-1	250	10	120	160	13
3	-1	+1	-1	+1	-1	150	20	120	160	13
4	+1	+1	-1	-1	+1	250	20	120	140	19
5	-1	-1	+1	+1	+1	150	10	140	160	19
6	+1	-1	+1	-1	-1	250	10	140	140	13
7	-1	+1	+1	-1	-1	150	20	140	140	13
8	+1	+1	+1	+1	+1	250	20	140	160	19

For experimental measurements of the RT of the material in the extruder, we used a colour indicator (colourant) “3291 Carnine” (Germany). The colourant was added to every sample at a concentration 3 g/kg.

The colour of the extrudates was measured with a “Pye Unicam PU 8800” spectrophotometer

2.3. Measurement of the RT of the material in the extruder

The minimum and maximum RT of the product was determined by the curve describing the RT of the particles as shown by Lambrev *et al* (1995). The average residence time can be calculated by the formula:

$$\bar{t} = \frac{\int_0^\infty t_i C(t_i) dt}{\int_0^\infty C(t_i) dt} \approx \sum_{i=0}^{n} t_i . C(t_i) . \Delta t \qquad (1)$$

where: **t_i** - is the average RT of the particle in interval **i**

$C(t_i)$ - is the value of the RTD function at time **t_i**

Δt - is the range of the intervals in which the RTD is divided

t is constant for every interval

The variance of the RTD is calculated by the formula:

$$s^2 = \sum_{i=1}^{n} \left(t_i - \bar{t}\right)^2 p(t_i) \qquad (2)$$

We can determine the probability **P(t)** that a certain random variable can belong to a certain interval with the help of the method of the rectangles in the following way:

$$P(t_i) = \int_a^b C(t_i) dt = \sum_{i=1}^{n} \Delta t . C(t_i) \qquad (3)$$

The variation **s^2** for a discrete random variable divided in **n** intervals can be calculated by the formula:

$$s^2 = \sum_{i=1}^{n} \left(t_i - \bar{t}\right)^2 . \Delta t . C(t_i) \qquad (4)$$

Van Zuilichem *et al,* (1988) used the Peclet number to characterise the structure of the flow in the extruder. During extrusion the hypothesis of plug flow combined with simultaneous mixing of the material can be used. This can be determined with diffusion laws applied to cases of axial longitudinal diffusion or to combined longitudinal and crosswise diffusion.

When evaluating the mixing process in the extruder (Van Zuilichem *et al,* 1988), we used the non-dimensional Peclet number:

$$Pe = \frac{v.l}{D_L} \quad \text{or} \quad Pe = \frac{v.l}{D_R} \qquad (5)$$

where: **l** is the characteristic dimension of the machine

v is the linear velocity of the material

DL and **D**R are the coefficients of longitudinal and crosswise diffusion.

If **Pe** → ∞ the diffusion model is converted into a model of longitudinal movement of a nut of product in which a screw is being rolled up.

If **Pe** → 0, than the machine can be described as one in which an ideal mixing is performed. Levenspiel (1969) found that when mixing bulk products one finds mainly lower values of D_L/v, as the relationship between the dispersion of the distribution function of the RT in the barrel and this ratio is:

$$s^2 = \frac{2D_l}{v.l} = \frac{2}{Pe} \tag{6}$$

This model can define the process of mixing of semolina products, because such products are conveyed in a greater part of the screw length. If we assume that every pitch of the screw is a separate chamber with certain dimensions that is connected to the next chamber and that m is the number of the existing chambers (or cells), then the relationship between **m** and the dispersion s^2 of the RTD can be described in the following way:

$$\frac{1}{m} = 2\frac{D_L}{v.l} = s^2 \tag{7}$$

when $m \leq 1$ the chamber model is a model of ideal mixing, and when $m \to \infty$, it is a model of ideal displacement, *i.e.* displacement without mixing.

3. Results and Discussions

The average results of three experiments are shown in table 3. Five regression equations were obtained, describing the relations between the parameters of optimisation and the independent variables.

Table 3

Average results of three parallel experiments

Number ofexperiment	t_{min}, s	t_{max}, s	$\bar{t}$, s	s	s^2	$m.10^{-3}$
1	29	128,33	75,31	16,55	274	3,6
2	12,43	58,50	36,36	7,67	58,82	17
3	16,33	59,90	36,78	7,26	575,0	17,3
4	16,50	106,33	61,42	14,97	224,1	4,4
5	27,46	119,93	71,89	15,41	237,47	4,2
6	25,16	124,33	70,19	16,52	272,91	3,66
7	18,53	82,66	48,25	10,67	113,85	8,78
8	12,33	57,50	35,23	7,52	56,55	17,6

$$t_{min} = 19{,}22-2{,}61X_1-3{,}31X_2+1{,}63X_3-2{,}07X_4+1{,}12X_5-2{,}14X_1X_4-2{,}14\,X_2X_3 \tag{8}$$

$$t_{max} = 92{,}18-5{,}52X_1-15{,}58X_2+3{,}91X_3-18{,}22X_4+10{,}84X_5-10{,}43X_1X_4-10{,}43X_2X_3 \tag{9}$$

$$\bar{t} = 54{,}50-3{,}57X_1-8{,}96X_2+1{,}99X_3-9{,}35X_4+6{,}57X_5-5{,}63X_1X_4-5{,}63X_2X_3 \tag{10}$$

$$Pe = 19{,}17.10^{-3} + 2{,}201X_1+4{,}926X_2-2.05X_3+8{,}93X_4+4{,}201X_5+1{,}97X_1X_3+4{,}35\,X_2X_3 \tag{11}$$

$$m = 9{,}57+1{,}098X_1+2{,}45X_2-1{,}008X_3+4{,}458X_4-2{,}118X_5+0{,}973X_1X_3+2{,}178X_2X_3 \tag{12}$$

The interpretation of the regression equations can be improved significantly with the graphical presentation of the dependent variable as a function of two independent variables (iso lines), when the other independent variables are fixed. These results are shown in figures 1 to 4.

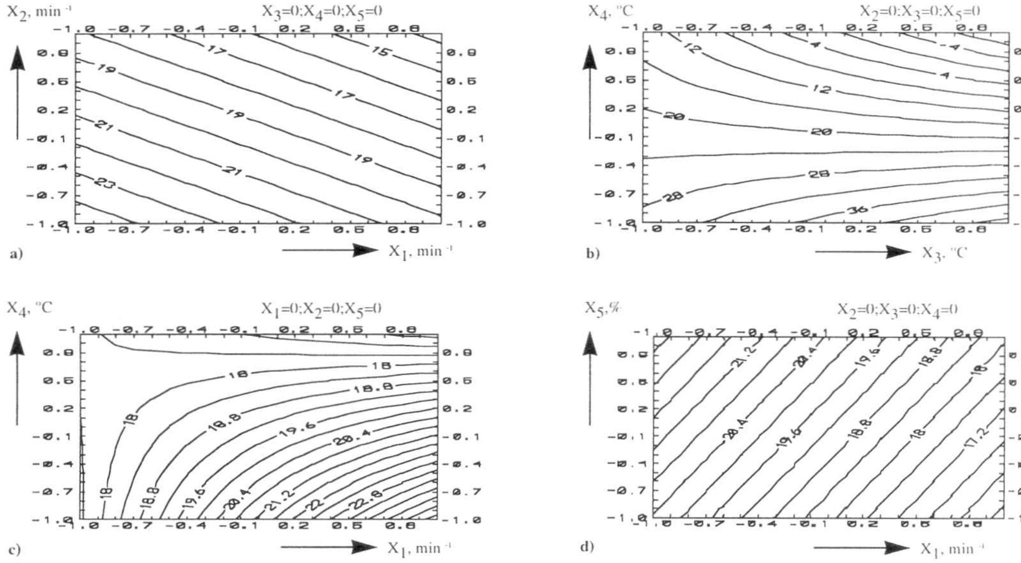

Figure 1

3.1. Influence of the process parameters on the minimum residence time

When the rotational speed of the feeding screw is 15 min^{-1} ($X_2=0$), the temperature in the second zone of the barrel is 130°C ($X_3=0$), and the initial moisture of the raw material is 16% ($X_5=0$), increasing the temperature of the die leads to a decrease in the minimum RT (figure 1b). From equation (8) it follows that the temperature of the die has a negative influence on t_{min}, but the great decrease of t_{min} (figure 1b) is more a result of the increasing rotational speed of the pressing screw than of the temperature of the third zone (figure 1a,b).

When we have a constant moisture content of the wheat semolina and the rotational speed of the pressing screw of 200 min^{-1} (figure 1c), we can see that the temperature of the second zone has a positive effect on the minimum RT while the temperature of the die has a negative effect as it decreases t_{min}

(figure 1c). The lowest value of the minimum RT, which leads to largest output of the machine, is achieved when the rotational speed of the pressing screw and the temperature of the die are, respectively, 250 min^{-1} and 160°C, and the other independent variables are constant (figure 1b).

3.2. Influence of the process parameters on the maximum residence time

Increasing the rotational speed of the feeding and pressing screws contributes to a decrease of the maximum RT. Van Zuilichem *et al* (1988) and Bruin *et al*, (1978) have also noticed a decrease of **tmax** when the rotational speed of the pressing screw is increased, but Macco *et al*, (1982) found a decrease of t_{max} when the rotational speed of the pressing and feeding screws was increased.

When there are constant values of the temperature in the second and third zones of the barrel (respectively, 130°C and 150°C) and a constant moisture of the raw material (16%), there is a significant decrease of **tmax**, especially when the rotational speed of the pressing screw is 180 ÷ 250 min^{-1} and that of the feeding screw is above 17 min^{-1}.

The reasons for the decrease of the minimum and maximum RT are similar (figure 1a, 2a).

From equation (9) it follows that there is a linear relation between the temperature of the second and third zone of the barrel and the maximum RT in the die. From figure 1 it follows that the greatest decrease of t_{max} is achieved when the temperature of the third zone is increased from 140°C to 160°C and the temperature of the second zone is above 125°C, when the other independent variables are constant.

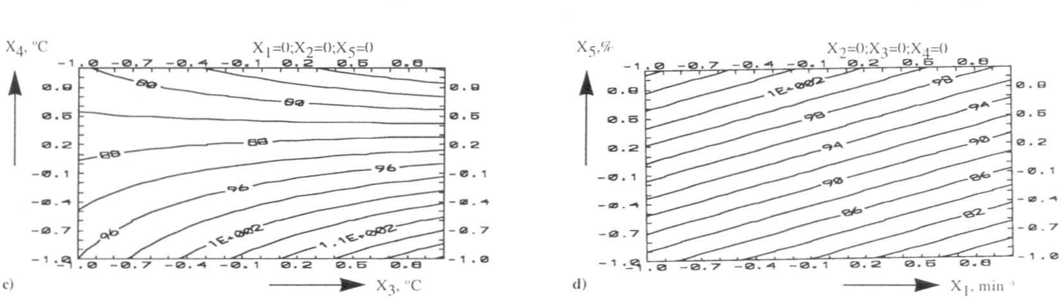

Figure 2

When the rotational speed of the feeding screw is 15 min^{-1}, the temperature of the second and third zone of the barrel are, respectively, 130°C and 150°C, and when the initial moisture is increased from 16% to 19% and the rotational speed of the pressing screw is increased from 150 to 225 min^{-1}, this leads to a decrease of **tmax**. Decreasing the rotational speed of the feeding screw below 15 min^{-1} and increasing the temperature in the second zone from 120°C to 140°C leads to an increase of the maximum RT.

3.3. Influence of the process parameters on the average residence time

The rotational speed of the feeding screw and the temperature in the die influence significantly the average RT of the material in the die (equation 10). Increasing the rotational speed of the feeding and pressing screws results in a decrease of $\bar{t}$. This phenomenon can be explained by the filling of the pressing screw with raw material and that is why we have a higher flow which decreases $\bar{t}$, especially when the rotational speed of the pressing screw is highest (figure 3). This is a result of the high speed of the flow on this extrusion regime. Similar trends have been published by Macco *et al* (1982) and others authors.

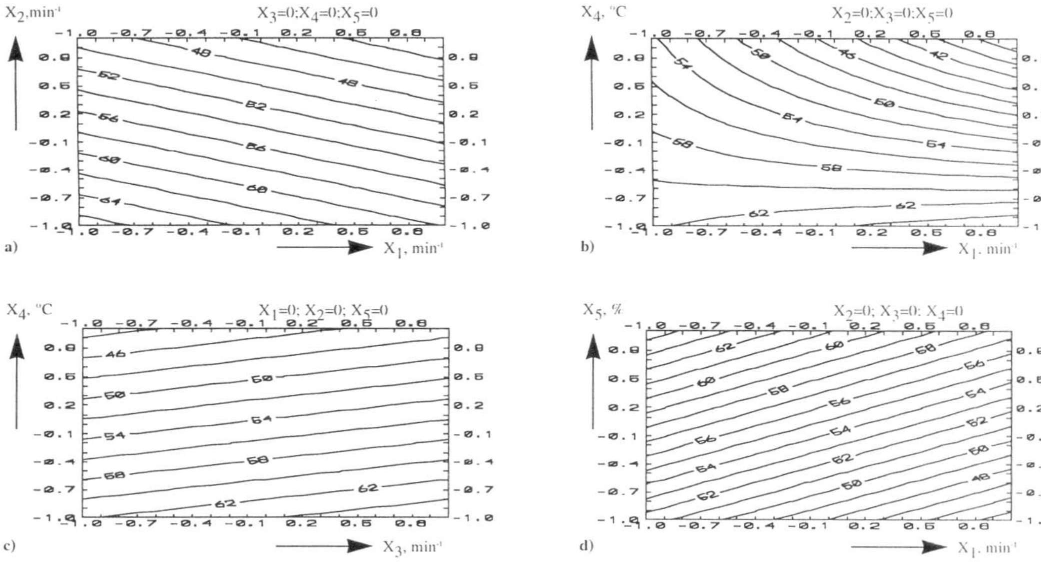

Figure 3

When we have the main level of the initial moisture at 16% and rotational speeds of the pressing and feeding screws of, respectively, 200 min^{-1} and 15 min^{-1}, the increased temperature of the second zone of the barrel and of the die contribute to decrease $\bar{t}$, (figure 3). This shows that the simultaneous increase of both temperatures assists a faster cooking of the material in the die.

When the rotational speed of the feeding screw, the temperature in the second zone of the barrel, and the temperature in the die remain constant (figure 3.d), we can notice that the average residence time is increased with the increase of the initial moisture, especially when the rotational speed of the pressing screw is above 225 min^{-1}, but it does not increase with the rotational speed of the pressing screw when the initial moisture is above 13%.

This means that when the moisture content is low and the rotational speed of the pressing screw is low, the product cannot fill the space between the threads of the screw, which results in slow and uneven flow in the die and an increase of $\bar{t}$.

The increase of the temperature in the second zone when the rotational speed of the feeding screw is lowest leads to an increase of $\bar{t}$ (figure 3d). This is a result of the low rotational speed of the feeding screw, when the speed of the pressing screw is constant.

3.4. Influence of the process parameters on the Peclet number and the number of cells in which the extruder is divided

From equation (11) it follows that the rotational speed of the pressing screw influences strongly the **Pe** number. Figure 4a shows clearly that the increase of the rotational speed of the pressing and feeding screws results in an increase of **Pe**. When the temperature of the second zone X_3 is constant and the temperature in the matrix is increased (figure 4c), we notice an increase in the **Pe** number, which is explained by the lowering of the viscosity of the melted semolina as a result of its cooking. The increase of the temperature in the second zone of the barrel and the initial moisture of the raw material lower the Pe number.

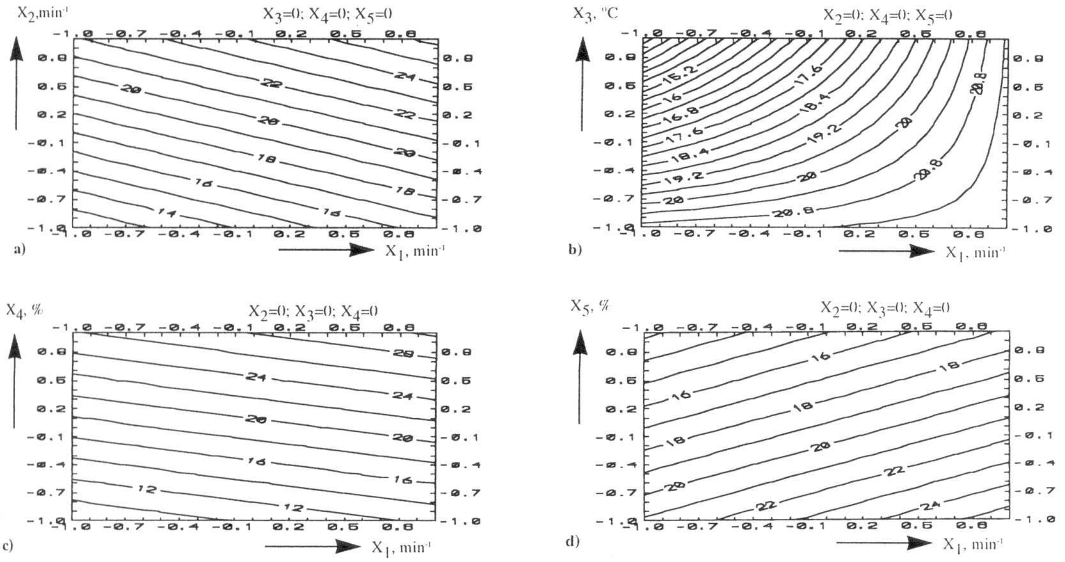

Figure 4

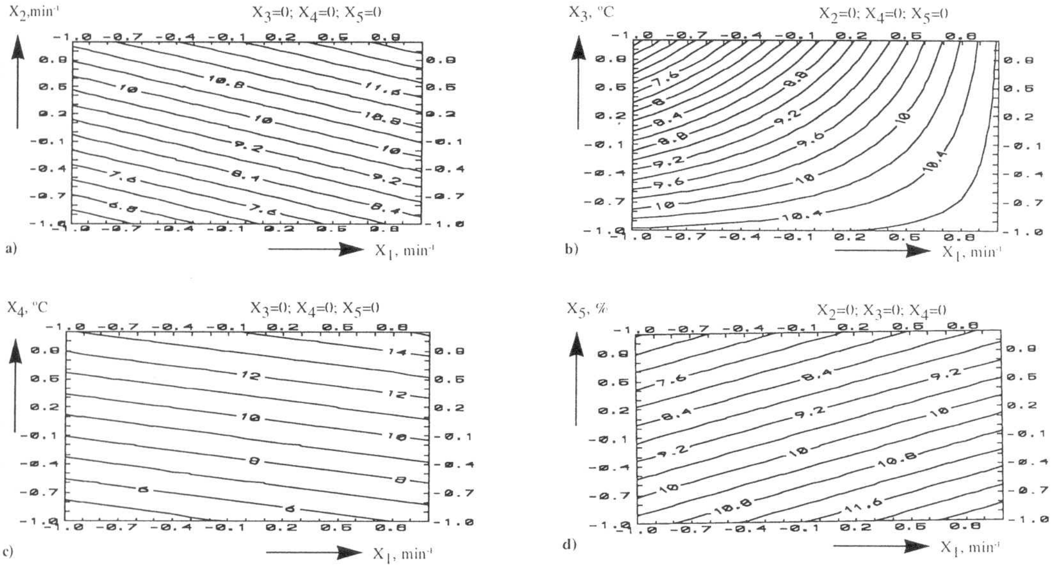

Figure 5

The lowest value of Pe in the investigated range during extrusion of wheat semolina was achieved when the temperature of the die was high or when the moisture content was high and the rotational speed of the pressing screw was lowest and the other independent variables were at their lowest level.

The number of cells **m** in which we can abstractly divide the extruder closely follows the variations of the **Pe** number (equation 12), (figure 5).

4. Conclusions

A simplified model for classification of the mixing properties of the extruder was established.

Regression models were proposed which describe the relation between the rotational speed of the pressing and feeding screws, the temperature in the second zone of the barrel and in the die and the initial moisture of the wheat semolina with the dependent variables being the minimum, average and maximum residence time of the product in the extruder, the **Pe** number and the number of cells.

A single screw extruder with ratio **L/D=20**, can be classified as an "*ideal*" mixer.

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