Effect of propeller use on residence time distribution (rtd) in single-screw cam-flow rice semolina extrusion

Yanush Chalamov[1], *Apostol* Simitchiev[1*], *Ventzislav* Nenov[1], *Angel Danev*[2], *Hristina Andreeva*[2]

[1] Department of Machines and apparatuses for food industry, Technical faculty, University of Food Technology, 4002 Plovdiv Bulgaria
[2] Department of Computer science and technologies, Technical faculty, University of Food Technology, 4002 Plovdiv Bulgaria

Abstract. The influence of the speed of the feeding (Nf) and main (Nw) screw, the moisture content of the material (W) and the temperature of the die (Tm) on the average residence time ($\bar{t}$) and the Peclet number (Pe) in single-screw extrusion of rice semolina using a propeller were investigated. A computer system with a camera was used to continuously read the colorant saturation as a tracer pulsed into the feed zone of the extruder. The differential distribution curves of dwell times were constructed. The responce surface methodology with an orthogonal central compositional plan was used. Regression equations were obtained describing the influence of the selected independent variables on the average residence time ($\bar{t}$) and the Peclet number (Pe). It has been found that the use of a propeller increases the mixing capability of the extruder and brings it closer to the ideal mixer.

1 Introduction

Extrusion subjects food raw materials to continuous processing with varying levels of temperature, compression, shear forces and stresses. In this way, final products with desired characteristics are obtained. Regardless of the continuous process, mixing and homogenizing, the individual layers of materials are subjected to different levels of shear forces, pressure and temperature. This is because the individual particles do not pass through the extruder at the same time, resulting in a different distribution of residence time in the extruder.

During extrusion cooking, grain raw materials have the behavior of non-Newtonian pseudoplastic fluids. The viscosity of the molten material in the machine depends not only on the temperature and the shear rate, but also on the residence time and the intensity of the mechanical force acting on it. Product movement in a single-screw extruder is not uniform because it is the result of three streams, which contributes to different particles of a product having different residence times inside the extruder. Investigating and determining the time that material particles spend inside the extruder is essential to analyze the thermal and mechanical impact that occurs during extrusion.

The terminology of Residence Time Distribution (RTD) was introduced in 1953 by Danckwerts as a means of describing non-ideal mixing of fluids in chemical reactors [1]. This basic concept of Danckwerts has been cited over 2,500 times, sparked discussion about material behavior in the machine, and gave way to an area in engineering chemistry studying the mixing of reactor materials.

In the scientific literature on mixing reactors, RTD methods have been discussed in more than 5000 scientific papers. RTD techniques are used to evaluate flow systems [2][3].

Models used in chemical engineering aim to obtain residence time distribution (RTD) curves. These RTD curves are generated using data obtained by measuring the concentration of a tracer species mixed in a small concentration with the base material injected at the extruder inlet. This approach makes it possible to describe the extruder as a combination of chemical reactors, stream flow and ideal mixing apparatus. [4]. Two main methods are used to introduce a marker indicator into the system: pulse and step [5], [6]. Pulse experiments are the momentary introduction of a tracer through an orifice into the system during the process. This is effective in conserving the material as well as ensuring that the system is not overloaded by changing material concentration. The resulting response is a differential distribution curve that begins and ends at the zero value of the tracer concentration [7].

The time history inside the extruder or distribution function of exit times is given by E(t) as follows:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} = \frac{C(t)}{\sum_0^\infty C(t)\Delta t} \quad (1)$$

* Corresponding author: asimitchiev@uft-plovdiv.bg

where:

C(t) – time tracer concentration, t.

Mean residence time was calculated according to the formula:

$$\bar{t} = \frac{V_f}{Q_v} = \int_0^\infty t.C(t)dt = \frac{\int_0^\infty t_i\, C(t_i)dt}{\int_0^\infty C(t_i)dt} = \frac{\sum_{i=0}^{\infty} t_i.C(t_i).\Delta t}{\sum_{i=0}^{\infty} C(t_i)} \quad (2)$$

where: V_f – the full volume of material in the extruder, m^3; Q_v - volumetric flow rate of extruder, m3/h; t_i – mean residence time of particle in the interval, s; $C(t_i)$- value of RTD curve for part of the time t_i; Δt – the division intervals of the RTD curve.

The variance of the RTD curve was calculated according to the formula:

$$s^2 = \int_0^\infty (t-\bar{t})^2 E(t).dt = \sum_0^\infty (t_i-\bar{t})^2.E(t).\Delta t \quad (3)$$

Van Zuilichem et al [8] used the Peclet number to characterize the flow structure in the extruder. The hypothesis of a combination of simultaneous movement of two types of flows in the extruder can be used during extrusion - an ideal extrusion flow /piston type/ and an ideal mixing of the material. This can be determined by diffusion laws applied to the cases of axial-longitudinal diffusion or to combined longitudinal and transverse diffusion.

To evaluate the mixing process in the extruder, a dimensionless Peclet number was used according to the formula:

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

where:

v – linear flow velocity of the material, m/s; L – characteristic length, m; D_L or D_R longitudinal or cross mass diffusion coefficients.

The Peclet number gives information about the mixing ability of the extruder.

Studying and knowing the distribution time for which the product is in the extruder provides a better understanding of the influence of the individual working parts of the extruder and process variables on the extruded material [9,10,11], the degree of mixing of the material layers [12,13], process scaling [14] and optimization of both the process, and the extruder [15,16].

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.

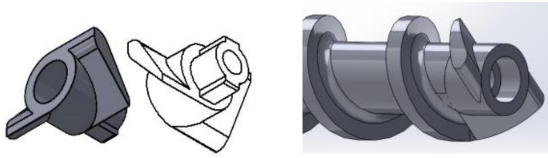


Fig. 1. 3D sketch of propeller

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 residence time distribution in single-screw extrusion of rice semolina.

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 12.6% 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 were grounded, 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 Mean residence time

Mean residence time was calculated according to the formula (2). The natural colorant "Carmoasin" was used as an indicator, and the samples were made according to the scheme in fig. 2.

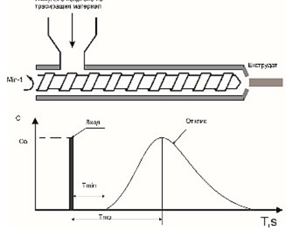
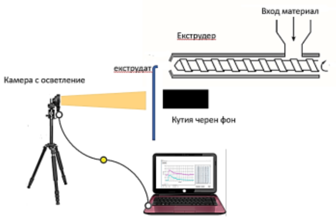
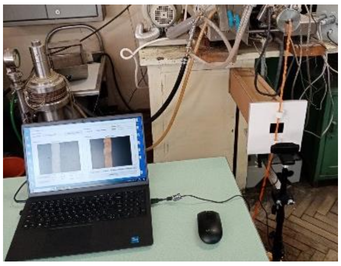


Fig. 2. Schematic of determining the residence time of the material in the extruder

The results presented in this research are obtained using a specially assembled computer system, which is made up of a hardware and a software part. The completely experimental setting is shown on Figure 3. The hardware part consists of the following components – portable computer (1) for processing row images; high definition digital camera (2) which is used for capturing certain amount of frames for further processing and a special developed tool (3) for unifying the background behind the object of interest (the extruded product) preventing any reflections or glares. The software part consists of a special developed standalone program (4) for Windows OS and is used for digital image processing and extraction the features of the object of interest.



(a)



(b)

Fig. 3. Scheme **(a)** of the experimental setup for measuring the color of extrudates, **(b)** working configuration of the setup

After stabilization of the extruder operation, a sample of 5 g of material plus colorant at a ratio of 3 g/kg was pulsed and the start time t was recorded while the chamber began to take pictures of the extrudates flowing out. After passing the entire quantity of colored material and reaching the coloring of the extrudates as in the initial moment, the camera is stopped. The resulting image database is processed to obtain the color of the extrudates and the corresponding times. The coloring is determined by the Lab system. Value **a** was used.

2.4 Peclet number Pe

Mean residence time was calculated according to the formula:

$$Pe = \frac{2}{S^2} \quad (6)$$

where:

S - variance of the RTD was calculated according to the formula:

$$S^2 = \sum_{i=1}^{n} \left(t_i - \bar{t}\right)^2 \Delta t . C(t_i) \quad (7)$$

where:

$C(t_i)$ - value **a** of the RTD curve at time t_i.

2.5 Statistical analysis

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 behaviour 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:

$$Y = b_{o+} \sum_{i=1}^{k} b_1 . x_1 + \sum_{1<i<j<k} b_{ij} . x_1 . x_j + \sum_{i=1}^{n} b_{ii} . x_i^2 \quad (8)$$

Two identical central orthogonal composite plans of a type 2^4+2.4 +star were carried out. The first series of experiments were 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 level	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

3.1 Mean residence time $\bar{t}$

Table 2 show the results of the statistical analysis of variance (ANOVA-test) for mean residence time $\bar{t}$ without and with the propeller at a confidence interval of 95% and a significance level α=5%.

Table 2. ANOVA-test for mean time distribution $\bar{t}$ without and with propeller

Without propeller			With propeller		
Source	F	P	Sourc e	F	P
A:Nf	2,03	0,18	A:Nf	0,26	0,62
B:Nw	3,97	0,07	B:Nw	0,16	0,69
C:W	0,04	0,85	C:W	0,05	0,82
D:Tm	0,92	0,35	D:Tm	0,35	0,56
AA	3,15	0,10	AA	3,52	0,09
AB	0,60	0,45	AB	3,88	0,07
AC	0,52	0,48	AC	0,28	0,61
AD	4,27	0,06	AD	3,61	0,08
BB	1,14	0,31	BB	0,00	0,96
BC	1,45	0,25	BC	0,23	0,64
BD	2,83	0,12	BD	9,25	0,01#
CC	9,52	0,01#	CC	9,11	0,01#
CD	7,87	0,01#	CD	0,09	0,77
DD	10,4	0,00#	DD	8,10	0,01

- statistically significant (P≤0.05);

In the experiments without propeller, three of the effects were statistically significant as their P-value was less than or equal to the chosen significance level (P=0.05 at α=5%). After eliminating the non-significant effects, the following adequate equation was obtained for the change in mean time distribution $\bar{t}$ without a propeller.

$$\bar{t}_1 = 576{,}445 + 1{,}192.W^2 + 0{,}168.W.Tm - 0{,}034.Tm^2 \quad (9)$$

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

$$\bar{t}_2 = 150{,}492 - 0{,}022.Nw.Tm + 1{,}414.W^2 \quad (10)$$

The mean residence time is an indicator of the residence of the layers of material in the extruder and the relationship between the volumetric flow rate and the free volume of the screw space.

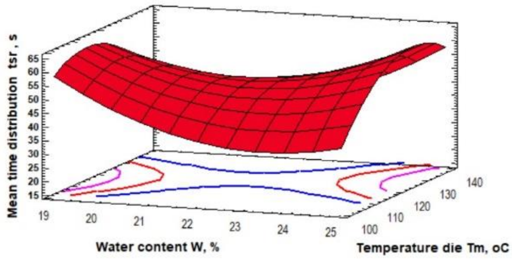
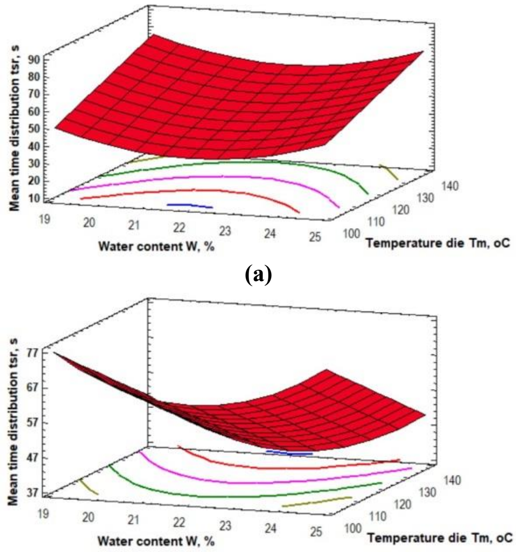


Fig. 4. Response surface of the mean residence time $\bar{t}$ in the extruder $\bar{t}$ depending on the moisture content of the material and the temperature of the die without a propeller

In non-propeller extrusion, the mean time has minimum values in the center of the plan at about 22,5% material moisture content. With larger and smaller values of water in the extrudates, the average time increases. The temperature of the die has the same influence, as we have minimum values at around 125°C. A minimum residence time of 32-35 s is obtained at 22.5% moisture content and 125°C mold temperature, and the maximum values of the mean time of 76 s are obtained at a mold temperature of 114 °C and a material moisture content of 19%. Obviously, the structure of the molten extruded material is most affected by these two parameters in the investigated range of experiments.

Two statistically significance effects were obtained in the experiments with a propeller. After removing the insignificant effects, the following adequate equation for the mean residence time using the propeller was obtained:

Increasing the working screw speed leads to a decrease in the mean residence time as well as an increase in the temperature of the die. With the same regimes, with an increase in the working screw speed from 190 to 249 min^{-1}, the mean time decreases between 20 and 30 % at the same values of the die temperature.



(a)

(b)

Fig. 5. Response surface of the mean residence time $\bar{t}$ in the extruder depending on the moisture content of the material and the temperature of the die with a propeller.
(a) N_w =190 min^{-1}; **(b)** N_w=249 min^{-1}

Minimum value of the mean residence time $\bar{t}$ =31,6 s is achieved a: die temperature 105°C, moisture content of material 21.5% ,working screw speed of 192 min^{-1}.

3.2 Peclet number Pe

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

Table 3. ANOVA-test for Peclet number (Pe) without and with propeller

Without propeller			With propeller		
Source	*F*	*P*	Source	*F*	*P*
A:N_f	0,22	0,64	A:N_f	2,89	0,117
B:N_w	2,21	0,16	B:N_w	0,00	0,944
C:W	0,35	0,56	C:W	0,87	0,369
D:T_m	0,14	0,71	D:T_m	1,36	0,268
AA	0,41	0,53	AA	3,77	0,078
AB	0,08	0,78	AB	0,42	0,531
AC	2,42	0,14	AC	0,88	0,367
AD	0,25	0,629	AD	2,02	0,182
BB	0,00	0,98	BB	5,88	0,03#
BC	2,09	0,17	BC	2,67	0,130
BD	3,90	0,07	BD	44,2	0,00#
CC	12,4	0,01#	CC	5,88	0,03#
CD	7,78	0,02#	CD	11,2	0,00#
DD	15,6	0,01#	DD	19,2	0,00#

- statistically significant (P≤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 Peclet number (Pe) when extruding without a propeller:

$$Pe_1 = -17{,}792 \; - 0{,}128.W^2 - 0{,}015.W.Tm + 0{,}006.Tm^2 \qquad (11)$$

In the case with a propeller, five 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:

$$Pe_2 = 148{,}777 \; - 0{,}001.Nw^2 + 0{,}001.\mathrm{Nw.Tm} - 0{,}083.W^2 + 0{,}018.\mathrm{W.Tm} + 0{,}006.Tm^2 \qquad (12)$$

The increase in the working screw speed in combination with low moisture content of the raw material leads to an increase in the Peclet number Fig. 6.

The response surface has a saddle-shaped shape, as the increase in the working screw speed has a negative effect on the Peclet number, respectively a positive effect on mixing and bringing the process closer to the ideal mixer. This influence is stronger at low values of the moisture content of the material. At a material moisture content of 19% and a die temperature of 105℃, increasing the working screw speed from 190 to 249 min^{-1} leads to a decrease in the Péclet number from 0.006 to 0.002 i.e. significantly by good mixing of the layer materials.

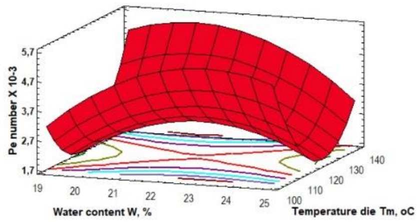
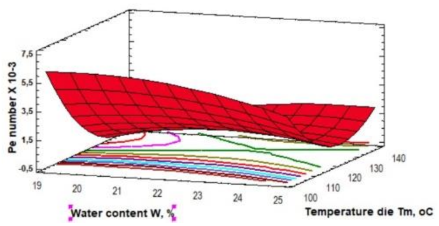
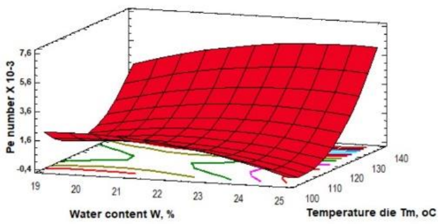


Fig. 6. Response surface of the Peclet number Pe in the extruder depending on the moisture content of the material and the temperature of the die without a propeller



(a)



(b)

Fig. 7. Response surface of the Peclet number Pe in the extruder depending on the moisture content of the material and the temperature of the die with a propeller
(a) N_w =190 min^{-1}; **(b)** N_w=249 min^{-1}

The maximum value of the material at low values has a negative effect, reaching minimum values and then an increasing action with respect to the Peclet number. We have the minimum values of Peclet's number between 100-115℃. As an absolute minimum, Pe=0.00024 is in the following mode - working screw speed N_w=249 min^{-1}, moisture content of the material W=24%, die temperature of the die T=108℃.

The use of propeller has a positive effect on reducing the Peclet number and leads to an increase in the mixing, especially at high working screw speed.

3.3 Correlation analysis between mean residence time and Peclet number

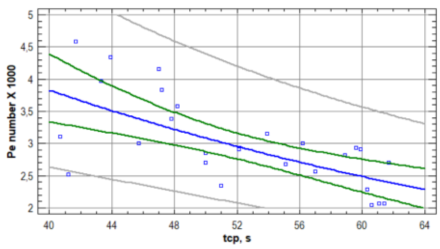
Correlation is a term from mathematics that generally indicates a probabilistic stochastic relationship between two random variables. Correlation analysis between two measurable quantities, mean residence time and Peclet number, show the degree of interrelationship between them through the correlation index.

Table 4 shows the regression equations and the correlation index for the two variants.

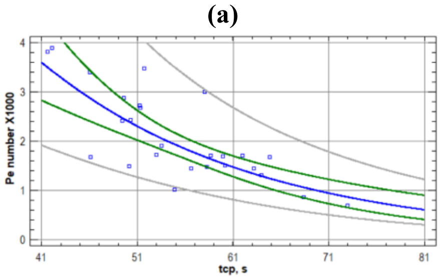
Table 4. Regression equations and correlation index between Peclet number (Pe) and mean residence time ($\bar{t}$)

Propeller	no	yes
Equation	$Pe_1 = e^{(2{,}20-0{,}022.\bar{t})}$	$Pe_2 = e^{(3{,}31-0{,}045.\bar{t})}$
Correlation index	0.68	0.78

The correlation between Peclet number and mean residence time without (a) and with (b) the use of propeller are shown in Figure 8.



(a)



(b)

Fig. 8. Correlation between Peclet number and mean residence time without **(a)** and with **(b)** the use of propeller

At these levels of correlation index (R=0.68) when running without a propeller there is a significant correlation (0.5<R<0.7) between the two variables while when using a propeller (R=0.78) there is high correlation (0.7<R<0.9).

In both cases, as the mean residence time increases, the Péclet number decreases, respectively, there is better mixing and the extruder comes closer to an ideal mixer. With the use of a propeller, the gradient of the reduction of Peclet number is inversely correlated with the average residence time, in contrast to the experiments without a propeller, i.e. the performance of the extruder is more stable at different average residence time.

Conclusion

Adequate mathematical models were obtained by using the response surface method, 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 mean residence time and Peclet number.

The use of a propeller leads to an increase in the mean residence time in the extruder between 8 and 14%. The minimum and maximum values are 31.6 s and 87 s with propeller and 29 s and 76 s without propeller.

The use of a propeller leads to a reduction in the Peclet number, which is a criterion for mixing the layers of material in the extruder. With propeller the lowest Peclet number value is Pe=0.00024 and without propeller Pe=0.00241.

The use of a propeller increases mixing in the extruder and brings it closer to an ideal mixer compared to extrusion without a propeller.

A correlation analysis was made between the mean residence time and the Peclet number showing the degree of interrelationship between them through the correlation index.

In the experiments without propeller, the correlation between the two variables is significant (R=0.68), and in those with the propeller, it is strong (R=0.78).

In both cases, as the mean residence time increases, the Péclet number decreases, respectively, there is a better mixing and the extruder comes closer to an ideal mixer. With the use of a propeller, the gradient of the reduction of Peclet number is inversely correlated with the average residence time, in contrast to the experiments without a propeller, i.e. the performance of the extruder is more stable at different average residence time.

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