Simulation of dough kneading process, for a kneader with vertical arm and mobile vat

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ABSTRACT

This study approaches tridimensional numerical simulation for bread making dough, kneaded with a vertical arm and mobile vat machine – Diosna SPV 160 AD model, with the purpose of pinpointing how the chafe of vat's bearings influence the energy consumption and the rheological properties of dough.

The first part of the paper contains a comparative analysis of kneading curves obtained on the same kneader, but using a vat with chafed bearings and one with new bearings. For the resulting diagrams, was registered data from the kneader's engine, using a measuring device for current intensity. Based on these kneading curves, dough rheological properties can be compared with the ones given by Brabender device.

In the second stage, it is verified a mathematical model which measures the mechanical energy transferred to the dough for the analysis of previously obtained measurements on the vats of Diosna SPV 160 AD machine.

The final part of the paper presents the breaking stress a vat's wall is subjected to during kneading process. The results were obtained by generating a tridimensional model with the parameters from the analysis of the kneading curves, using Simulation in Solid Works program. Due to the graphic results, it is possible to interpret the differences between energetic fluctuations and applied forces to the system, factors with a major impact on the final dough used in industrial bread making.

It is important to specify that the efficiency of the kneading process is influenced also, by the imposed kneading conditions, the amount of introduced air, the quantity of added water and the quality of the flour being used. In this study, these conditions were maintained constant for the tests. Knowing that the speed with which the energy is transmitted to the dough is influenced by its consistency which is interdependent with the kneading process, it is extremely important that the dough kneading process to be optimum, in the established amount of kneading time.

The comparative analysis between the two kneading processes has concluded with a rise of 22% of the maximum resistant moment at the kneading arm and a lower consumption of electrical energy at the kneader's engine, with 15% for the vat with new bearings.

The main objective for the 3D simulation of the kneading process for bread making dough is the complex study of dough behavior during kneading.

KEY WORDS: dough, kneading process, kneading curve, torque, mechanical energy, simulation.

1. INTRODUCTION

The rheological properties of wheat flour doughs are largely governed by the contribution of starch, proteins and water [2,3]. The main characteristic of wheat flour is that, mixed with water, it has the ability to form a continuous macromolecular viscoelastic network. By hydrating the protein content it forms gluten which acts as a balloon and traps the carbon dioxide gas bubbles produced by fermentation.

The mixing process is the crucial operation in bakery industry by which the wheat flour, water, and additional ingredients are changed through the mechanical energy flow to coherent dough. The dough properties are strongly influenced by the way of their mixing [3,9,11]. The dough development is a dynamic process where the viscoelastic properties are continuously changing. Consequently, this causes very low correlations between the dough rheological parameters (development time, stability of dough, breakdown, and others) obtained from different mixers. Furthermore, the lab mixing devices like Farinograph or Mixograph do not exert identical mixing actions not only between them but also in comparison with industrial mixers [5]. Some of the values can be well correlated. Farinograph stability is well correlated to the mixing requirements of dough [8] while the Mixograph development time is well correlated to the bakery mixing time [12]. Due to the dissimilarities between laboratory analysis (such as the dough development, energy or stability) and industrial application, the flour's profile and its behavior has to be validated through tests in the industrial bread making process with a closer inspection of the real behavior of dough and the characteristics of the end product.

From the industrial view, the requirements for the mixing process can be formulated as a cost effective way for processing of dough with proper quality. The requirements of the doughs for the mixing energy are related to the dough strength; therefore the costs of the end-products of mixing are different. Different industrial mixers can be evaluated through their efficiency [10].

The energy consumption (work input) for the dough formation at the peak resistance depends on the flour used, mixer speed, and mixer type. During mixing, the energy flow and the hydration processes are accompanied with a temperature increase. The temperature growth is dependent on the speed of mixing [9], but it is assumed that heating of dough during mixing is influenced by the type of the flour used and also by the type of mixer. Through the determination of the proper energy input, optimal changes during mixing can be probably achieved (in the case of one type of mixer). It is possible in this way to manage the process of dough developing.

The difficulties in the determination of an exact model for energy flow to the arising dough system and thus defining the mixing requirements of flours with a defined composition (mainly in starch and protein characters) reside in the complexity and variability of emergent mixing forces inside the dough during its deformation (shear, stress, extension, creep), where each mixer type imparts mixing energy by a dissimilar way [4,6].

The purpose of the paper is to demonstrate the necessity of a monitoring system, attached to a conventional industrial dough kneader, in order to control the kneading process, technologically, as well as technical.

The main objectives of this study are: 1) the analysis of the differences between a kneading process using a vat with new bearings, versus a kneading process using a vat with chafed bearings; 2) the influence of equipment usage on the optimum forming of dough; 3)the comparative analysis between the energy level introduced in both experiments; 4) the analysis of the obtained results, after introducing the data in a 3D simulation.

2. MATERIALS AND METHODS

For the experiments, it was used a type of wheat flour with 0.480% ash, from the 2015 production, produced by SC 7 Spice SA – Valcea. The characteristics of the flour are shown in table 1. The dough was prepared from 100 kg of wheat flour and 58 l of water, with a kneading time of 11 minutes, using an industrial kneader - Diosna SPV 160 AD model provided with a spiral kneading arm and mobile vat. The dough preparation was accomplished at room temperature, 20–22ºC.

Table 1

Physio – chemical characteristics of the flours used in the experiments

Flour type	Moisture content, [%]	Wet gluten, [%]	Ash, [%] d.s.	Gluten deformation [mm]	Acidity, [degrees]	Falling number, [sec]	Gluten index
FA - 480	13,4	29	0,48	3,5	2	318	92

Flour acidity is expressed in acidity degrees and is determined using the water suspension method, titrated with sodium hydroxide 0.1 n solution.

For the comparative analysis between vats with different abrasive wear of the bearings, it was used a device for measuring and data acquisition. The working principle of this method consists in connecting the measuring and data acquisition device to the engine of the kneader, where it measures the consumed electricity by the engine during kneading, a consumption that is growing/descending depending on the opposition force of the dough at the kneading arm, and more so on the torque at the kneader's working arm. Before starting the kneading process, a clamp which registers the intensity of the current, was connected to the power supply of the engine. The clamp was also connected to a data acquisition device (Supco type –figure 1b), which downloads real time information on a computer. The registered signals were filtered based on the intensity's current variation, and the variation curves for the dough consistency during kneading, were drawn, at a second's interval.

In order to filter the obtained data, functions like max, min, average, count and others in the Excel program were used. The next step was to correlate the measuring unit between the one used for the Brabender farinograph (figure 1a), which is Newton multiplied with meter, and the one on the results obtained by the consumption at the kneading arm. This stage made it possible to verify the correctness of the interpretation of the acquired data.

At first, the mixer was left working without load (out-current), in order to establish the energy losses of the kneader, which were decreased from the final calculation of the torque (Nm) consumed by the spiral blade, in relation with the opposing force of the dough.

Considering the general relation for calculating the necessary driving power on the working arm, it can be written:

$$P_m = M_m \frac{\pi n}{30} \text{ [Kw]} \quad (1),$$

where: Mm is the resisting torque at the kneading arm, maximum, respectively medium and Pm is the corresponding power, [11].

For finding the power consumed by the mixer's engine, the following relation was used:

$$P_m = \sqrt{3} U I cos\phi \text{ [Kw]} \quad (2),$$

where: U is tension of the current, I is the intensity of the current and which is the value measured by the clamp and is the power factor.

In order to establish the consumed power by the kneading process, without the energy losses, the next relation was used:

$$P_{mf} = P_m - P_{mg} \text{ [Kw]} \quad (3),$$

where: P_{mf} is the consumed power only for the kneading process, P_m is the total power consumed by the mixer's engine and P_{mg} is the consumed power of the engine, on out-current.

Knowing the consumed power for the kneading process and the angular speed described by the kneading arm, it is possible to calculate the medium torque, as it follows:

$$M = \frac{P_m}{\omega_m} \text{ [Nm]} \quad (4),$$

where: M is the opposing medium torque at the kneading arm, P_m is the power consumed by the engine only for the kneading process and ω_m is the angular speed of the arm when kneading [7].

a. b.

Fig. 1 - a. Brabender farinograph; b. Portable device used for measuring the consumed current when kneading dough

For the second stage of the paper, the same data acquired with the portable device, was used in a different mathematical model, in order to calculate the amount of mechanical energy transferred to the dough. The following expression was used:

$$E = \frac{CNt}{M} \text{ [J]} \quad (5)$$

where: C is the average torque (Nm), N is the angular velocity (rad/sec), t is the mixing time (sec), and M is the weight of the mixed dough (kg). The amount of heat absorbed by the dough during mixing was determined by calculating the difference between the temperatures of the dough at the beginning and the end of the mixing (°C), multiplying by the heat capacity of the dough (calculated as the weighed sum of the heat capacity of each component (1.9 J/g/°C) and multiplying by the weight of the mixed dough [1].

For the simulation presented in the third part, the dough was formed of flour and water added in 58% proportion. The numerical results were obtained for a density of dough (ϱ) of 1200 kg/m^3, the angular speed of the kneading arm being 180 rpm and the angular speed of the vat being 15 rpm.

The 3D simulation of the kneading process for bread making dough has as main objective, the study of bread dough behavior during kneading. In the first phase of this modeling the geometrical model is generated, with which the final simulation is run. The steps for this phase can be followed in figure 2.

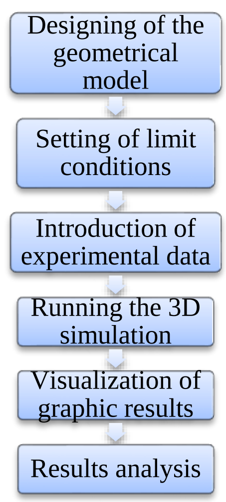


Fig 2 - Steps for obtaining the 3D simulation in Solid Works

In this tridimensional study, the flowing conditions were considered to be for balance. In order to simulate the dough's behavior, during the kneading process, the following hypothesis were considered: the flow corresponds to the equilibrium state, it is laminar and isotherm, the vat is full with dough, the dough is considered to be incompressible and viscous, non-newtonian, with negligible inertia. The gravitational effect is taken into consideration only for large quantities of dough, in the case of the limit section, the effect of gravity, being negligible.

3. RESULTS AND DISCUSSION

Mechanical development of dough is obtained when, in the kneading process, a sufficient quantity of mechanical work is transferred to the dough. Through the movement of the kneading arm, in the mass of formed dough speed gradients appear, which submit the dough to deformations and becomes a material with rheological characteristics governed by consistency, elasticity and extensibility.

The relation between force (F) and the moment of the force (M) for a body in rotation is written bellow.

$$M = Fb \tag{6}$$

$$F = M/b \tag{7}$$

where: M is the moment, F is the force and b is the arm.

In figure 3, it is explicated the difference between the resistant torque at the kneading arm for a kneading process using a vat with 30% chafed bearings and one with new bearings.

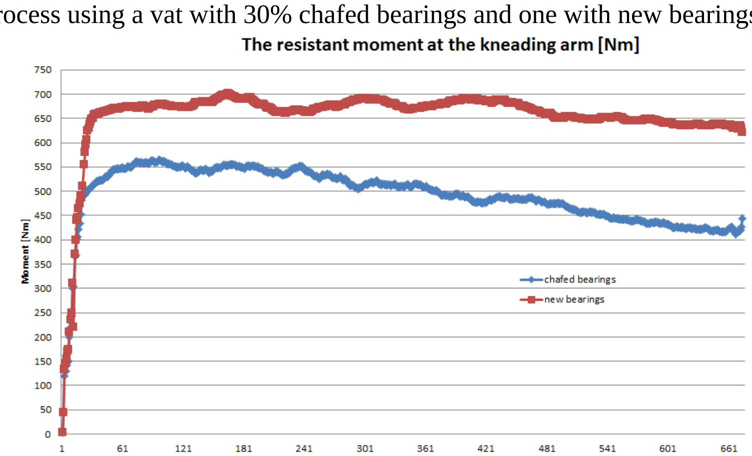


Fig.3 – The kneading curves drawn for a kneading process in a vat with chafed bearings, respectively, in a vat with new bearings

In the results, it can be observed an increase of maximum consistency with 18%, from 570 Nm to 700 Nm for the dough kneaded in the vat with new bearings, versus the one kneaded in the vat with chafed bearings, as well as doubling the stability time of dough with a better development of the gluten structure.

The speed with which the energy is transmitted to the dough in the kneading process is influenced by the dough's consistency.

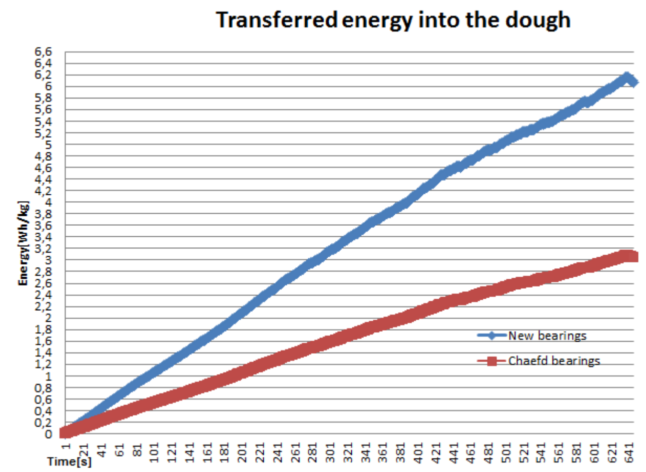


Fig. 4 – Curves describing the amount of energy introduced into the dough in the 2 tests

Here is how to calculate the friction factor: prior to making the dough, the exact temperature of the room, flour, and water, must be noted. After the dough is made, its temperature must also be noted. Because there are three main factors that influence the dough's temperature, it is necessary to multiply it by three. After doing this, it is necessary to add the three temperatures - room, flour, and water and subtract the sum from the temperature of the dough multiplied by three. The result is the energy or heat of the friction generated either manually or mechanically [13].

In order to verify the mathematical model with which the energy is transferred to the dough, method illustrated in table 2 was used.

Table 2

Mathematical model of calculation for friction [13]

Operation	Chafed bearings	New bearings
Dough temperature obtained [˚C]	26	28,5
Multiplied by 3	78	85,5
Room Temperature [˚C]	24	24
Flour Temperature [˚C]	24	24
Water Temperature [˚C]	22	22
Sub Total	70	70
Subtract Total from	78	85,5
	70	70
Friction/Energy [◦C]	8	15,5

In order to calculate the amount of introduced energy into the dough, the experimental data were introduced in the following general formula [1]:

Friction Temperature [°C]*Weight [g]*Calories = J*g*°C (8)

(Temperature friction [C]*Weight [g]*0.0027)/1000=Wh/Kg/°C (9)

The formula was applied for both studied cases, as it is illustrated bellow:

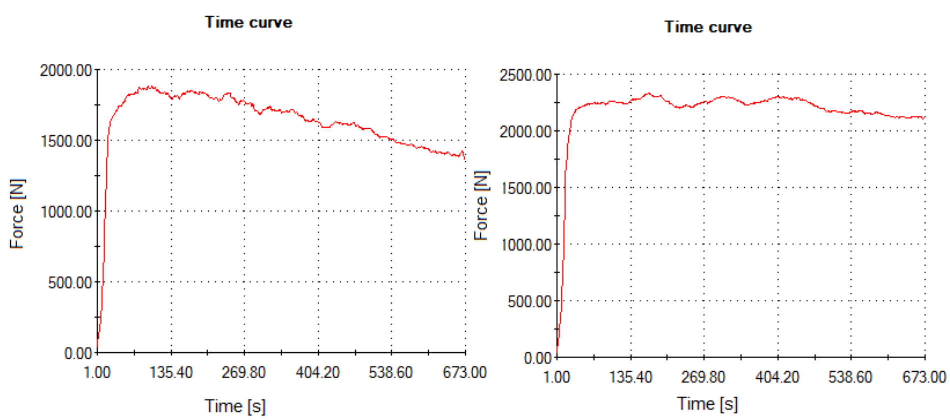
1. Chafed bearings:

(8*158000*0.0027)/1000 = 3.41 Wh/Kg/°C (10)

2. New bearings:

(15,5*158000*0.0027)/1000 = 6.61 Wh/Kg/°C (11)

The experimental data was introduced in the simulation program in order to simulate the applied forces by the dough on the vat's walls.



a) b)

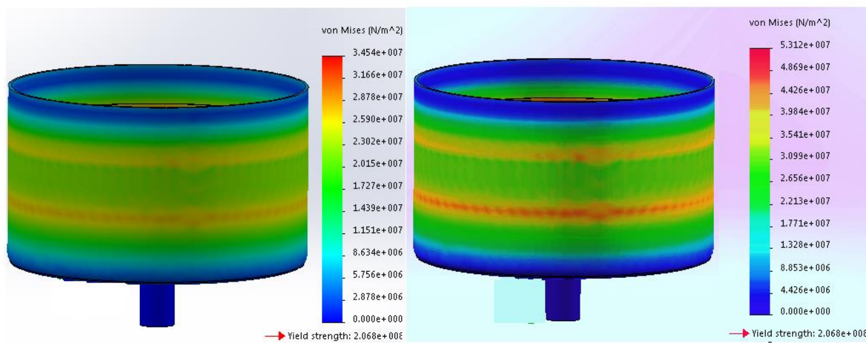
Fig. 5 – Graph which shows the applied forces by the dough on the vat's walls: a) forces applied for the vat with chafed bearings; b) forces applied for the vat with new bearings

In the third part of the research, it was run the simulation for the kneading process, through which the effect of the tensions that appear on the surface of the vat and kneading arm, was analyzed using Von Mises stress method.

Von Mises theory proposes that the total strain energy can be separated into two components: the volumetric (hydrostatic) strain energy and the shape (distortion or shear) strain energy. It is proposed that yield occurs when the distortion component exceeds that at the yield point for a simple tensile test. This is generally referred to as the Von Mises yield criterion and is expressed as:

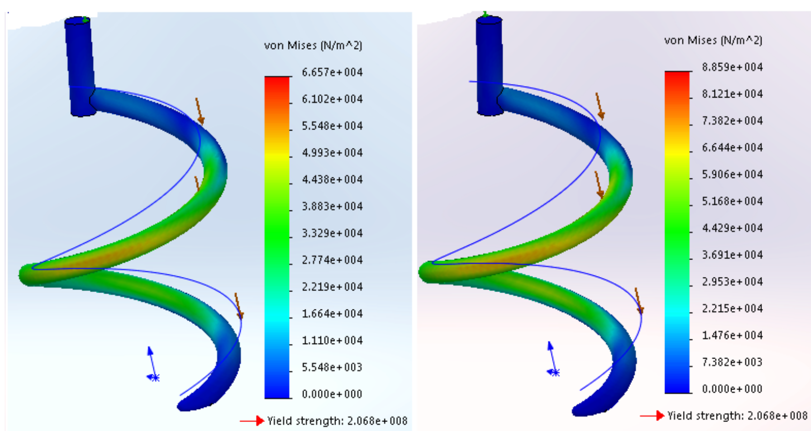
$$\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]\leq\sigma_y^2 \quad (12)$$

This assumes that yield occurs when the shear stress exceeds the shear yield strength: (σy). Since stress and strain are tensor qualities they can be described on the basis of three principal directions; in the case of stress these are denoted by , σ1, σ2, and σ3.



a) b)

Fig.6 – 3D Simulation for tensions on the surface of the vat during kneading process: a) vat with chafed bearings; b) vat with new bearings



a) b)

Fig.7 – 3D Simulation for tensions on the kneading arm during kneading process: a) tensions applied on a kneading arm, at the vat with chafed bearings; b) tensions applied on a kneading arm, at the vat with new bearings

Because the section where the dough passes between the kneading arm and the vat's wall is small, the pressure is high, and the energy is directly proportional with the strain force for dough.

4. CONCLUSIONS

In the experiments, there are used: clamp which measures intensity of current, data and acquisition device, vat with new bearings and vat with chafed bearings, in order to register the differences between torques and energy introduced into the dough, in both experiments.

By replacing the chafed bearings at a vat for Diosna SPV – AD 160 kneader and registering the kneading curves with the system for measuring and data acquisition for the kneading process in both types of vats (with chafed and new bearings), a method for controlling the kneading process was identified. The kneading process was improved by creating a better structure for the gluten, i.e. better gas retention and also by reducing the electrical power consumption of the kneader.

In order to obtain a good quality dough, a very important aspect is not only the optimum amount of energy introduced, but also the speed with which it is applied to the dough. This paper demonstrates the importance of tolerance between the kneading arm and vat, tolerance responsible for transferring the energy to the dough. This way, to an optimum level of energy, it has to correspond a certain kneading time.

In figure 3 it can be observed that the stability time for dough kneaded in a vat with new bearings has doubled in time, which means the gluten network has substantially improved. The volume of the bread has grown from 520 cm^3 to 580 cm^3 as it can be seen in figure 8. It can also be observed in figure 3 a raise in maximum consistency, from 570 Nm to 700 Nm which means 17% more for the vat with new bearings, which also has a positive impact on the stability of dough.

In figure 4 it can be observed a raise in energy of 30% for the vat with new bearings, more energy introduced into the dough in the same time unit, even if the power consumption had equal value in both cases.

The 3D analysis shows differences in energy distribution on the vat's wall and on the surface of the arm. The data obtained in this study can be helpful in designing of kneading equipment and optimization of energetic consumption. The results obtained with the help of the 3D simulation for the kneading process can offer a prediction for the optimum parameters in the bread making process, which can improve it considerably.

By improving the kneading process, higher quality products are obtained. Especially improved, are the volume of the bread, the color of the core, a finer porosity and a tender structure, thanks to the superior rheological characteristic of dough (as shown in figure 8).

The quality of the end products is closely related to the technological parameters and the level of technology used in the process, which can improve significantly, the industrial process of bread making.

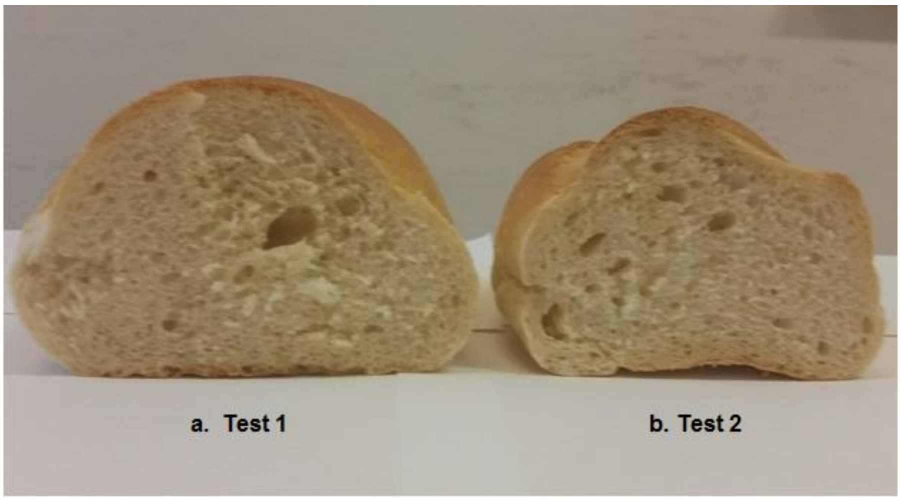


Fig.8 - Effect of energy input on bread quality: a) New bearings and energy input of 6.2 Wh/kg, b) chafed bearings 3.2Wh/kg

REFERENCES

[1].A.S. Contamine, J. Abecassis, M-H Morel, B. Vergnes, A. Verel (1995) - *Effect of mixing conditions on quality of doughs and biscuits, Cereal Chem 72;*

[2].Amemiya, J.I., Menjivar, J.A., (1992) - *Comparison of small and large deformation measurements to characterize the rheology of wheat flour doughs. Journal of Food Engineering 16, 91–108;*

[3].Gras P.W., Carpenter H.C., Andersen R.S. (2000) - *Modelling the developmental rheology of wheat flour dough using extension tests. Journal of Cereal Science, 31: 1–13;*

[4].Haraszi R., Larroque O.R., Butow B.J., Gale K.R., Bekes F. (2008) - *Differential mixing action effect on functional properties and polymeric protein size distribution of wheat dough. Journal of Cereal Science, 47: 41–5;*

[5].Hwang C.H., Gunasekaran S. (2001) - *Determining wheat dough mixing characteristics from power consumption profile of a conventional mixer. Cereal Chemistry, 78: 88–9;*

[6].Mani K., Eliasson A.C., Lindhal L., Trägardh C. (1992) - *Rheological properties and bread making quality of wheat flour doughs made with different dough mixers. Cereal Chemistry, 69: 222–225;*

[7].Voicu Gh. (1999) – *Processes and equipments for bakery*, Bren Publishing house, Bucharest;

[8].Wilson A.J., Wooding A.P., Morgenstern M.P. (1997) - *Comparison of work input requirement on laboratoryscale and industrial-scale mechanical dough development mixers. Cereal Chemistry, 74: 715–721;*

[9].Wilson A.J., Morgenstern M.P., Kavale S. (2001) - *Mixing response of a variable speed 125 g laboratory scale mechanical dough development mixer. Journal of Cereal Science, 34: 151–158;*
[10].Wooding A.R., Kavale S., MacRitchie F., Stoddard F.L. (1999) - *Link between mixing requirements and dough strength. Cereal Chemistry, 76: 800–806;*
[11].Zheng H., Morgenstern M.P., Campanella O.H., Larsen N.G. (2000) - *Rheological properties of dough during mechanical dough development. Journal of Cereal Science, 32: 293–306;*
[12].Zounis S., Quail K.J. (1997) - *Predicting test bakery requirements from laboratory mixing tests. Journal of Cereal Science, 25: 185–196;*
[13]Stanley P. Cauvain, Linda S. Young – *Technology of breadmaking, Second edition: 42.*