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Bread Dough Rheological Behavior Under the Influence of the Geometry of the Kneading Arms

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Abstract. *The main objective of this study is validation of a proposed mathematical model for the estimation of the influence of kneading arms geometries on rheological properties of dough. Two types of kneading arms are studied, both mounted on the same industrial kneader type. A tridimensional numerical simulation for dough kneading is used for obtaining the Eddy viscosity values, which were introduced in a mathematical model for calculation of the dough's resistant torque at the kneading arms, at 15 seconds time intervals. Real time torque diagrams developed by the kneading arms, were traced using a system for data acquisition and dough kneading control (SOPF), developed by BioTechnologiCreativ Company. These diagrams were used for mathematical model validation using the comparison between the torque values measured in real time and the ones obtained using the mathematical model, in which was introduced the Eddy viscosity value obtained with the 3D simulation. The obtained results have very similar values. With this study it is possible to predict the rheological behavior of dough during kneading process. Anticipation of the kneading diagram form can be helpful in the optimization of the entire technological process and the obtaining of dough with uniform consistency and optimal development during the stages of the manufacturing process.*

Keywords*: Eddy viscosity, dough kneading, rheology, 3D simulation, mathematical model*

1. Introduction

Dough is a visco – elasto – plastic body with a very complex behavior and its variations depend on a multitude of factors. In the case of wheat dough, consistency is a complex rheological property directly influenced by: viscosity, humidity, temperature, time and the proportions between dough phases (solid, liquid, gaseous), biochemical composition of flour, the added ingredients and the quantity of energy consumed at kneading, [1,2].

During the kneading process, the dough is subjected to extreme deformations, many of them exceeding the rupture limit, because of the speed gradients which appear in the dough mass, [3]. These influence dough's viscosity and its consistency implicitly. The number and speed with which intermolecular bonds are formed, depend on the intensity of the kneading action, the quantity of energy introduced into the dough and the speed with which it is imparted. Therefore, optimal, incomplete or excessive dough development is directly influenced by the kneading process, [4].

It is well documented in scientific literature that the speed with which the kneading diagram is formed, has a dramatic effect on the rheological behavior of wheat doughs, [5]. It is very important to take into consideration the fact that doughs obtained at different processing scales (laboratory, industrial) will have different properties. The same can be applied in the case of using different types of kneaders. In consequence, the rheological properties of the obtained doughs will present different characteristics.

In general, the speed of the kneading arm is known, but the configurations of both, kneading arm and vat are very different for different types of kneaders.

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These factors will lead to a different development for rheological properties of dough during kneading, even if the kneading arms have the same rotating speed. In rheological terms, kneaders apply different dough deformation forces, which are dependent of the vat and kneading arm geometries, [3].

Haraszi et. all [6], used a mixograph and farinograph to study in laboratory, the different effect they have over the rheological development of dough. They concluded that the geometry of the kneading arms and the way which they introduce energy into the dough, directly influence its rheological development. In their study, they present the different results obtained using the two laboratory scale devices, in similarly working parameters. The different development of the measured consistency diagrams reflects the importance of the kneading arm types and how these also influence the rheological behavior of dough in the case of industrial kneaders.

The use of rheological characterization of food materials is not only used for bread doughs [7-9], but also for many other materials, such as: pasta, liquids (wines, juices and sauces) [10,11], gels [12], yeast suspensions [13], collagen, starch [14], but especially for polymers and biopolymers.

In multiple research papers [15-17], the rheological behavior of dough is analyzed using rheometers for dough viscosity measurements, energy storage modulus, G’ and creep discharge, G’’. The rotational rheometers are the most used for studying dough viscosity. Viscometers with concentrically cylinders are also used even though they require a considerable effort for introducing the dough sample into the measuring device. Some researchers [18] modified a viscometer with concentrically cylinders, in order to facilitate the measurement of dough viscosity. The functioning principle of the modified viscometer is to measure the resistant torque of the working element, which results in a viscosity curve for the analyzed sample.

Wheat dough represents the study object for many researchers around the world, in food area and not only. The research in this field registers visible progress but enough questions remain unanswered regarding dough behavior and the determinants of its rheological properties.

Tridimensional simulation, next to mathematical model application and experimental measurements correlation, can lead to a better accuracy regarding the prediction of rheological dough behavior.

The main objectives of this paper, are: a) to prove the geometrical influence of the kneading arms over rheological dough development; b) to evaluate dough deformation speed distribution during kneading, using kneading process tridimensional simulation; c) to validate a mathematical model for calculating the resistant torque at the kneading arm, using dough viscosity.

The motivation for this study is the development of a technology which allows direct evaluation of the rheological behavior of dough in industrial environment, with which the optimization and control of kneading process parameters would be well facilitated.

2. Material and methods

2.1. Numerical simulation of dough kneading process

In a first stage, the ANSYS finite element program for 3D simulation was used for dough kneading process. Tridimensional geometries at scale, were designed for two kneader models, with double vertical working arms and mobile vats – model San Cassiano GDA 340, using a CAD program (Solid Works). The two models have working arms with different geometry, as it can be observed in Figure 1 and Figure 2. These were afterward transferred to the preprocessing package in the ANSYS program.

The following hypotheses for model running and discretization were applied: the vat is fully loaded with dough, the dough is a homogenous mass in full development, after the hydration period ended and is considered a non–Newtonian, incompressible material. It is already known that on the entire kneading period, the dough permanently changes its viscosity. If the kneading process is continued after registering a maximum viscosity value, the dough enters a decreasing curve. Taking these factors into consideration, the chosen model for the kneading tridimensional simulation was Carreau–Yasuda model.

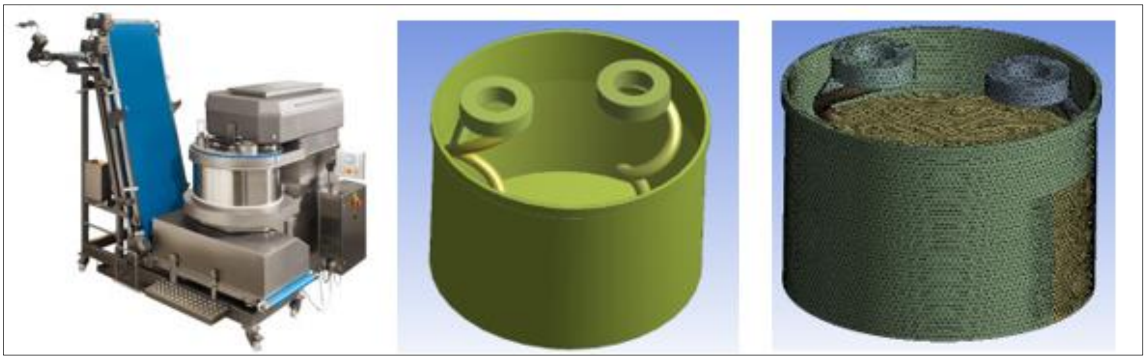


Figure 1. San Cassiano kneader, type GDA 340, with spiral kneading arms (Double Spiral)

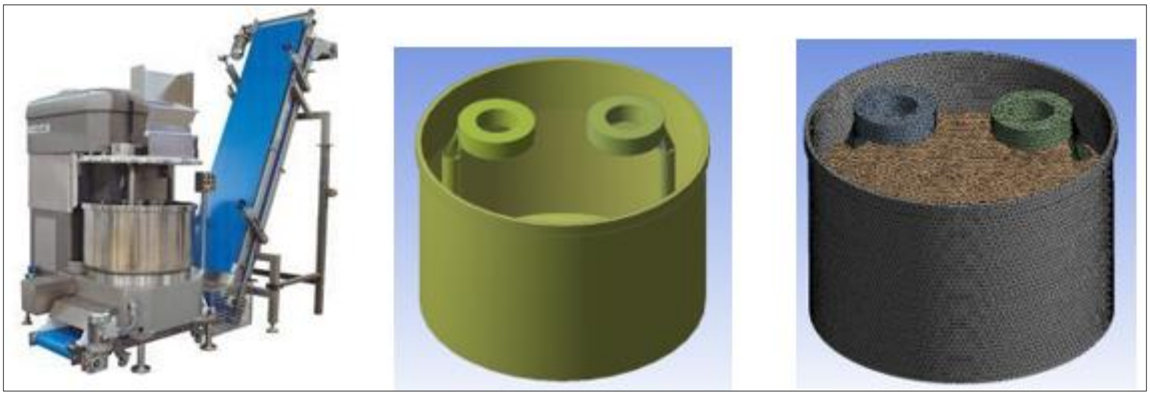


Figure 2. San Cassiano kneader, type GDA 340, with straight kneading arms (Hydra)

The fluid viscosity function, η, was modeled using Carreau–Yasuda constitutive relation (known for its capacity to represent multiple shear thinning behaviors),

$$\frac{\eta(\dot{\gamma})-\eta_\infty}{\eta_0-\eta_\infty} = [1+(\lambda\dot{\gamma})^a]^{\frac{n-1}{a}} \quad (1)$$

where: η is shear viscosity; η_0 – viscosity at zero shear rate; η_∞ - viscosity at infinite shear rate; λ - characteristic time; $\dot{\gamma}$ – shear rate; *a* –structural exponent (a=2 for the Carreau model) and *n* is the power index ($-1 \le n < 1$ for shear thinning fluid), [19].

The Eddy viscosity values obtained at the end of the simulation helps the interpretation of layers displacement in the dough mass during kneading.

The Eddy viscosity concept is based on similarity reasoning, with turbulence being a physical concept connected to viscosity. In the Navier – Stokes equation the viscous term is:

$$D_v = \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial U_i}{\partial x_j}\right)+\left(\frac{\partial U_j}{\partial x_i}\right)\right] \quad (2)$$

where: $\nu =$ kinematics viscosity, $U_i, U_j =$ the speed tensors, $x_j, x_i =$ transversal coordinates, [20].

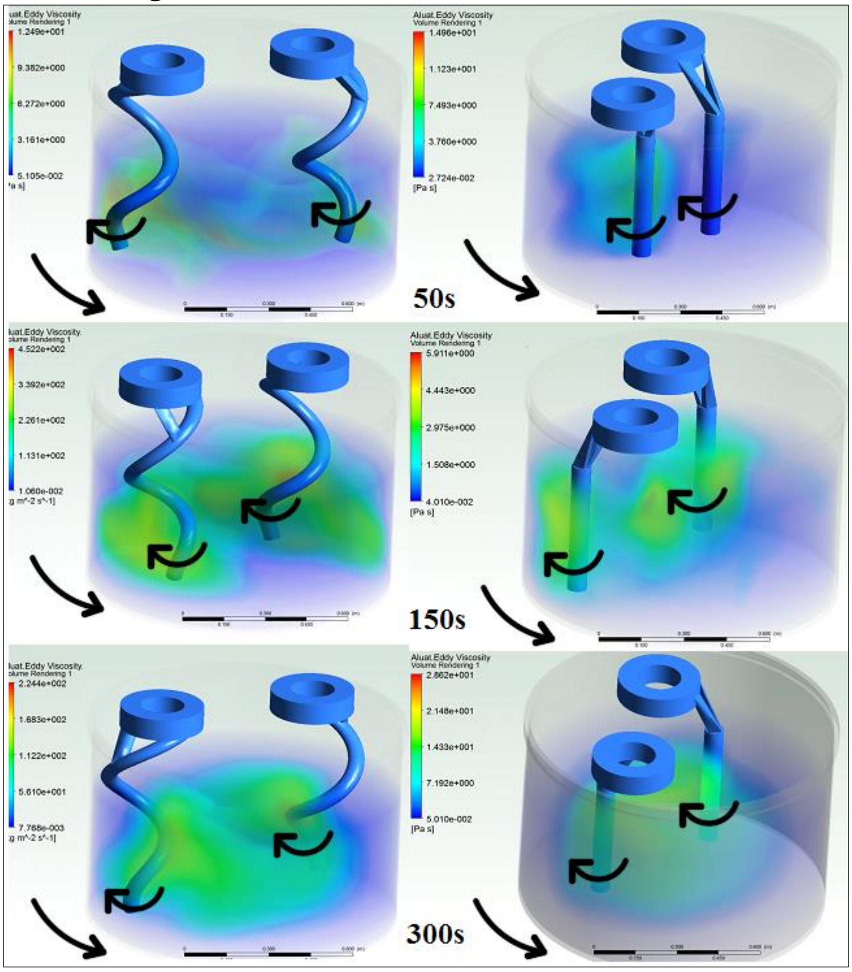
The following parameters were considered in order to run the simulation:

- dough is a homogenous mass composed of flour, water and salt, with a total weight of 216 kg;
- the simulation was run in dough stability conditions, at a constant density of ρ = 1200 kg/m^3 (determined using weighted average method);
- the temperature of dough was considered to be of 28ºC with viscosity dependent on the shear rate described by equation (1) and 30 Pa·s for dynamic viscosity of dough, [21];
- the rotation speed of the kneading arm was set at 180 rpm and the value for the kneader's vat at 30 rpm;

- the volume of dough was divided in a computational grid formed by a triangular unstructured network with a number of 145210 nodes, 644088 elements and 6103203 faces;
- the simulation run for 300 s, analyzing 3 positions of the kneading arm per second; the results of the simulation are shown in Figure 3.

2.2. Measuring the resistant torque at the kneading arms

The Eddy viscosity value obtained in the tridimensional simulation (Figure 3) for the two geometries of the kneading arms was introduced in a mathematical model with the purpose of determining the resistant torque at the kneading arms.



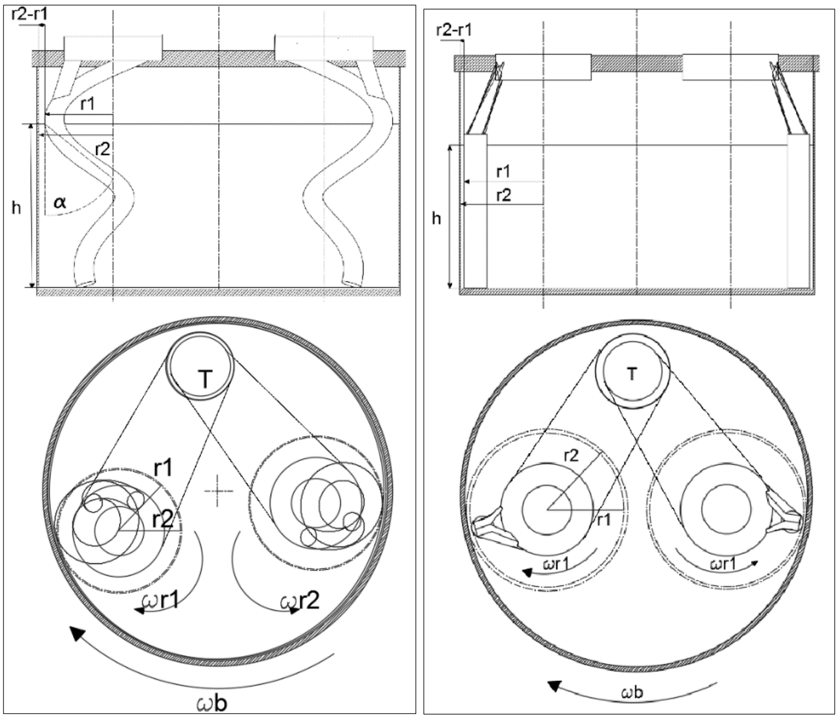
a. b.

Figure 3. Eddy viscosity for the two models, at 30 s, 150 s and 300 s of kneading time: a. spiral kneading arms; b. straight kneading arms

The mathematical model uses as starting point, the equations for viscosity determination with a rotating viscometer with coaxial cylinders, [22]. The kneading arms, both spiral and straight have a rotational movement around their own vertical axes, inside the kneader's vat, the entire ensemble being placed in a tridimensional Cartesian system. The vat rotates around its axes in opposing direction of the kneading arms.

The rotation speed of the kneading arms is 3 rot/s, meaning they reach 3 times in a maximum close point of the vat's wall. In this position, the resistant torque at the kneading arms is maximum and the mathematical model is applicable only for this situation.

In Figure 4 it is presented the geometry of the kneading arms, in which r_2 is the distance between the rotating center of the kneading arm and vat and r_1 is the radius at which the resistant torque at the kneading arm is measured.



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a. b.

Figure 4. Kneading arms geometry: a. spiral, b. straight

The following values are considered for the kneading arms: r_1 =0.24 m; r_2 =0.25 m; h = 0.5 m; ω_{r_1}=18.84 rad/s ; ω_{r_2}=18.84 rad/s; ω_b=2,09 rad/s . In the case of the spiral kneading arm type, there is also an angle, $\alpha = \cos(45°) = 0.525$, which represents the inclination of the kneading arm reported to the vat's axes.

The report between the shear stress and shear rate for non – Newtonian fluids is not linear and the viscosity values modify with the shear rate. Viscosity is defined as the relation between shear stress and shear rate, [16], as it is shown in equation (3):

$$\eta = \frac{\tau}{\gamma} \tag{3}$$

The mathematical expression for the shear stress is:

$$\tau = \frac{T}{2\pi r^2\ h} \tag{4}$$

where: *r* represents the radius at which the resistant torque at the kneading arm is measured, *T* is the resistant torque at the kneading arm and *h* is the depth at which the arm enters the dough mass, [22].

The shear rate is calculated with the following equation:

$$\gamma = \frac{\omega_r \bar{r}}{r_2 - r_1} \tag{5}$$

where: ω_r is the angular speed of the kneading arm, $\bar{r}$ is the average radius of r_2 and r_1, [16].

In the case of concentrically cylinders' viscometer, the viscous forces inside fluid lead to a shear force measured using a torque transducer connected to the inner cylinder, [23]. Material's viscosity can be measured using the resistant torque at the kneading arm and the rotational speed.

Viscosity for Newtonian materials can be calculated using the following formula:

$$\eta = \frac{T}{4\pi h\omega}\left(\frac{1}{r_2^2} - \frac{1}{r_2^2}\right) \qquad (6$$

Equation (6) is also known as the Margules equation and is generally applicable for Newtonian fluids, [21]. The curve generated for viscosity variations can be determined as the ratio between the shear stress and strain rate, [22].

In order to use the above relations, the notion of representative radius R_r was introduced as a function of the geometry of the kneading arm and vat, located on the contact areas (the areas of maximum closeness) between vat and the kneading arm. The expression has the following equation:

$$R_r = R_1 \left\{\frac{(2\beta^2)}{(1+\beta^2)}\right\}^{1/2} = R_2 \left\{\frac{(2\beta^2)}{(1+\beta^2)}\right\}^{1/2} \quad (7)$$

where: $\beta = \frac{r_2}{r_1} = \frac{0,26}{0,25} = 0.065\ m.$

Because the vat has rotational movement in both simulation and later experiments, the resultant angular speed can be calculated as: $\omega_t = \omega_a - \omega_v$. The rotational speed of the arm is 180 rpm and the vats at 20 rpm, for both kneaders. The resultant angular speed is $\omega_t = 16.74\ \text{rad/s}$.

Because the shear rate at representative radius R_r is independent of the fluid type, the representative shear rate is:

$$\dot{\gamma}_R = \omega \left\{\frac{[\beta^2+1]}{[\beta^2-1]}\right\} \quad (8)$$

The viscosity relation in which the representative radius is introduced, if equation (4) is divided by equation (8), becomes:

$$\eta = \eta_r = \frac{\tau_r}{\dot{\gamma}_r} = \frac{T}{\omega}\left(\frac{\beta^2-1}{4\pi\beta^2 r_1^2 h}\right) \quad (9)$$

The torque can be calculated using equations (4), (5) and (7), if the dynamic viscosity is known, [24].

The resistant torque at the straight kneading arms is calculated with the following expression:

$$T = \frac{\omega_t \eta}{\left(\frac{\beta^2-1}{4\pi\beta^2 r_1^2 h}\right)} \quad (10)$$

The resistant torque at the spiral kneading arms is calculated with the following expression:

$$T = \frac{\omega \eta}{\left(\frac{\beta^2-1}{4\pi\beta^2 r_1^2 h \cos 45°}\right)} \quad (11),$$

where: ω_t = 16.74 rad/s, $r_1 = 0,24\ m$, β = 1,083 m, h = 0.5m si η = $^{Ns}/_{m^2}$.

Using this data, and the geometry used for the mathematical modelling as shown in Figure 4, the dynamic development of the resistant torque at the kneading arms can be described.

2.3. Equipment used in the experiments and mathematical model validation

For the kneading process the following equipment was used: industrial kneader, developed by San Cassiano Italy, type GDA 340, Hydra, with double kneading arm and variable speed (0-150 rpm), on which was connected the system for kneading process optimization called SOPF, developed by BioTehnologiCreativ company, an electrical current intensity transducer and two flaps for ingredients discharge control. These can be observed in Figure 5.

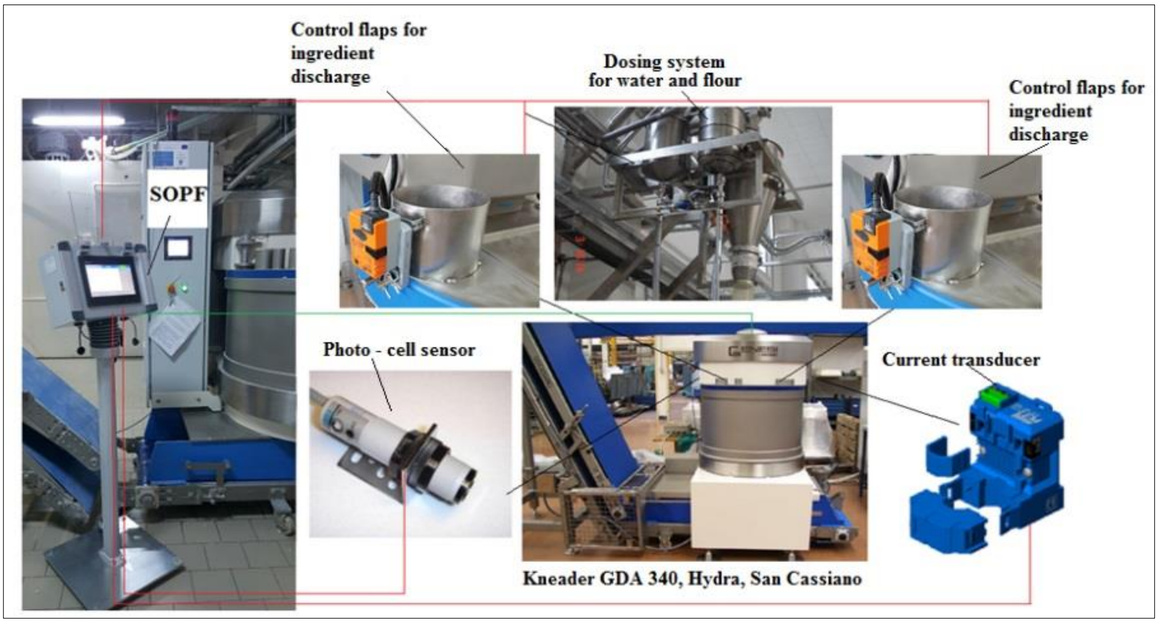

Figure 5. Equipment used for collecting experimental data, [23]

The SOPF system measures the electrical current intensity consumed by the kneading arm's engine. The following parameters are considered constant: electrical tension, U = 400 V, the power factor, cos Φ = 0.8 and the rotations of the kneading arms are measured using a rotation transducer. Before calculating the resistant torque at the kneading arm, working without load current consumption at the kneading arm's engine is measured and eliminated.

$$T = P/\omega \quad (12)$$

$$T = T_t - T_e \quad (13),$$

where: T_t – total resistant torque at the kneading arm calculated using the measurements of electrical current intensity consumed by the kneading arm's engine during the kneading process; T_e – the resistant torque at the kneading arm when working without load, [25].

3. Results and discussions

Development of Eddy viscosity in the entire mass of dough can be observed in Figure 3. Instants were taken for both kneading arms geometries, at 30, 150 and 300 s, respectively. Results show that curve values for resistant torque developed by straight kneading arms are greater than the one developed by spiral kneading arms. This is due to specific energy introduced into the dough, which in the case of spiral arms, the energy input is smaller per time unit.

An important aspect is dough's contact with the kneading arms which has a direct influence in dough development due to the specific dough's training movement with dough development in time and increase of viscosity. During kneading with spiral arms, the dough mass is progressively trained in the inferior part and dough's contact with the kneading arms is reduced.

In the case of straight arms, contact with dough during kneading takes place on the entire surface and once with viscosity increasing values, a greater mass of dough is trained in a rotational movement around the kneading arms.

The difference in viscosity values between the two analyzed kneading cases is shown in Figure 6. The straight arms displace and train a greater quantity of dough than the spiral arms, but also, the speed vector distribution in the layers of dough is uniform in the case of kneading with straight arms.

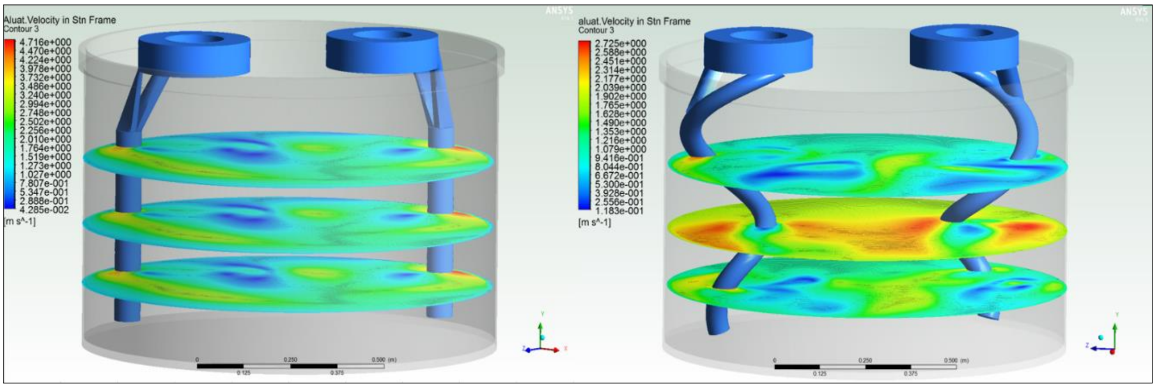

Figure 6. Tridimensional simulation of dough kneading showing development differences when using different geometries of the kneading arms; instant after 150 seconds of simulation

Results in Figure 6 show that in the kneading case with spiral arms, the speed in the central area reaches a maximum value of 2.75 m/s and is visibly superior to the speed of the other dough layers. In the case of straight arms, the speed inside dough layers reach a maximum value of 4.71 m/s on a much extended area in the entire dough mass.

Viscosity is directly dependent of dough consistency. By measuring viscosity values during the kneading process, the obtained curve development can be related to the consistency curve. After 150 s of simulation, the maximum viscosity values in certain areas is 3 times greater in the straight arms kneading simulation than in the spiral arms case. This can be related to a faster gluten network development and greater stretching and compression of dough during kneading with straight arms.

Because of the increased specific energy input per time unit, dough viscosity in the straight arms kneading case rapidly increases but when kneading is continued, the deformation speed exceed gluten network resistance limit and the elasticity of dough decreases progressively. Figure 7 shows deformation speed distribution for all the 40365 nodes at seconds 30 and 300 of kneading simulation for both types of kneading arms. The deformations which take place inside dough are different between the layers of the same dough and between the two kneading models. The relative movement of the layers increases near the surface of the arms and the speed gradient values are greater.

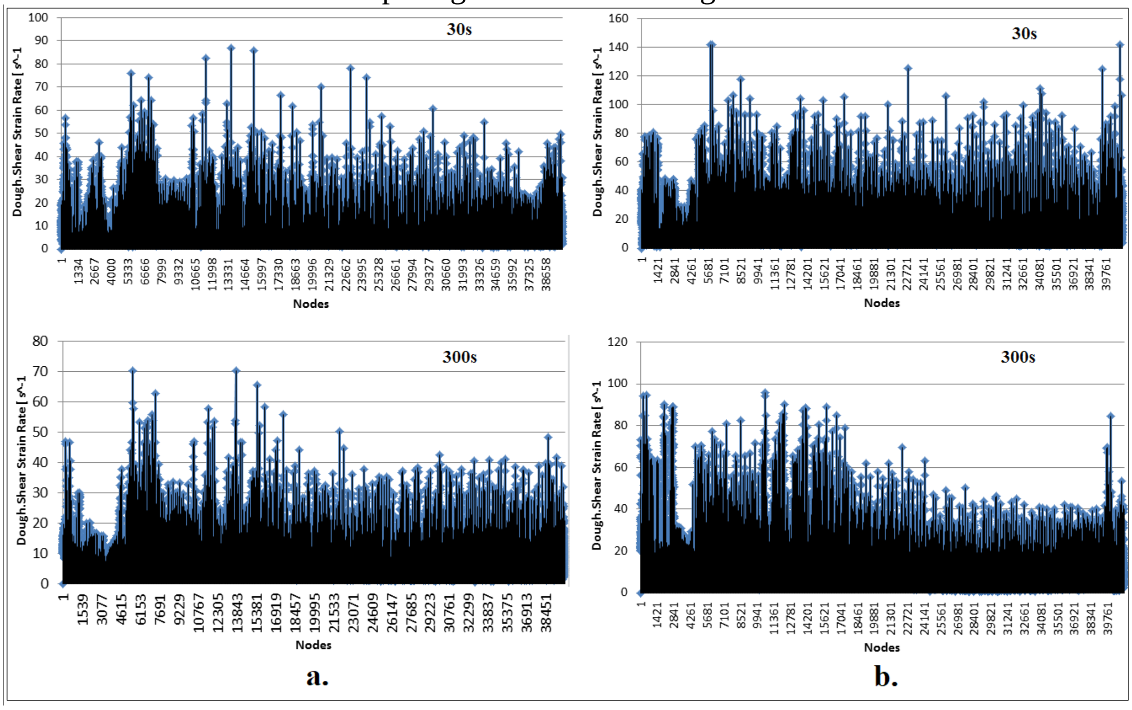

Figure 7. Speed deformation distribution in dough after 30 and 300 s for:
a) spiral arms; b) straight arms

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The results of this analysis show a small decrease in deformation speed at the end of the kneading process for the spiral arms case versus the straight arms, where the deformation speeds are reduced by half in some areas.

Next figures show the simulation of gluten network development during kneading with straight arms (Figure 8) and spiral arms (Figure 9).

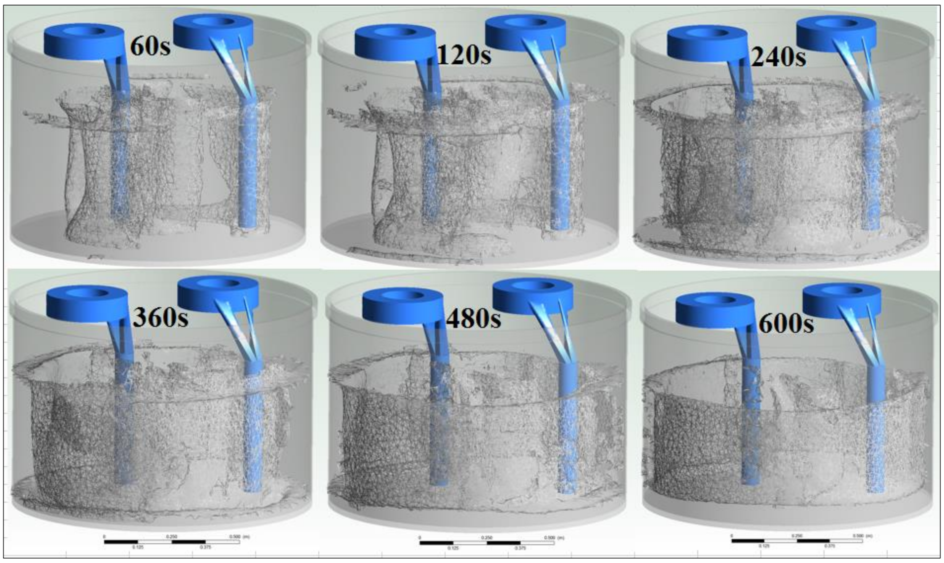


Figure 8. Dough development simulation with straight arms kneading

The gluten network starts forming rapidly around the kneading arms because the specific energy introduced into the dough is higher in this area. Around second 240 of kneading using straight arms (Figure 8) dough height reaches a maximum value which can be attributed to the maximum consistency point. After this point, the height of the dough decreases gradually due to the accelerated decrease of viscosity. The dough's quality properties continuously worsen by the end of kneading time.

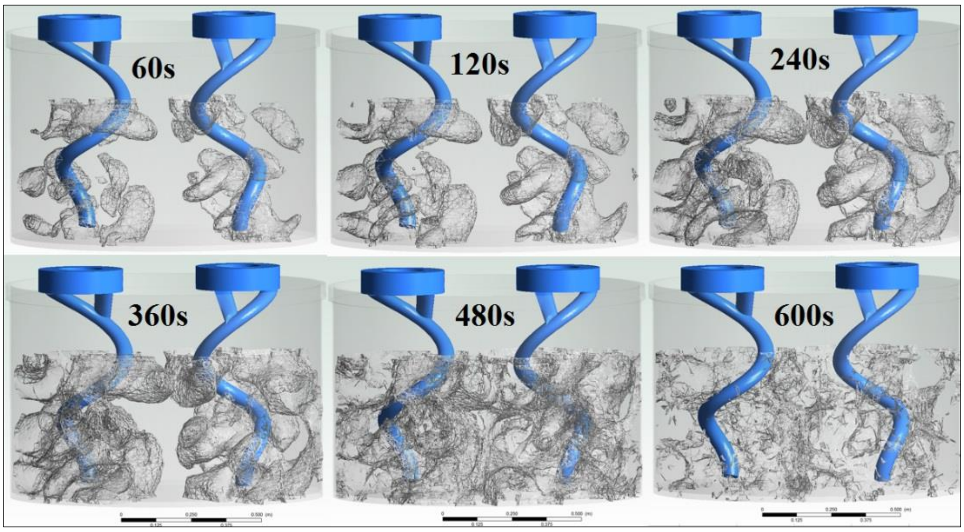


Figure 9. Dough development simulation with spiral arms kneading

In Figure 9 can be observed that dough development using spiral arms kneader is a gradual and constant process until second 360, marked by the massive gathering of dough around the kneading arms. After this point, the viscosity values are decreasing and the mass of dough tends to occupy the entire vat volume. Dough's resistance at the kneading arms is decreasing rapidly.

The results of this simulation offer the possibility to estimate the opposing force at the kneading arms and evaluate the energy consumption. It can be determined the moment when the dough reaches optimal development. Dough registers different developments when the geometries of the kneading arms are different. The simulation confirms the results obtained with the measured data in real time. According to the simulation viscosity values were higher for the dough kneaded with straight arms than for the dough kneaded with spiral arms. The torque diagrams obtained with SOPF system showed similar results.

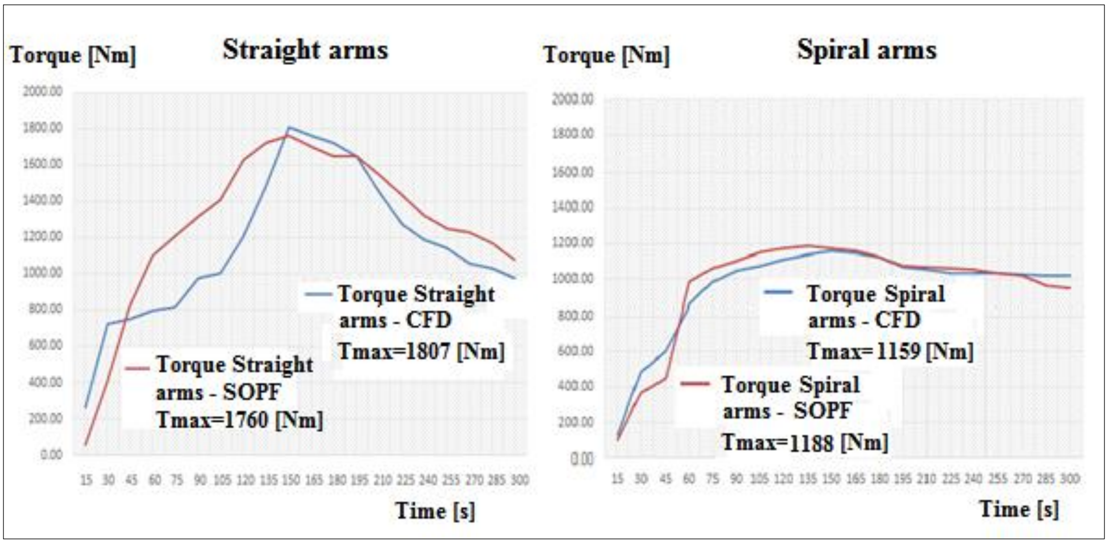
Table 1 shows 20 viscosity values taken at 15 s time interval for the two analyzed kneading cases. These values were introduced in the proposed mathematical model for calculating the resistant torque registered by the two kneaders using Computational Fluid Dynamics (CFD) and later compared with the resistant torque values obtained with SOPF.

The sum of resistant torque at the kneading arm for both kneading cases was obtained by applying the mathematical model in which the viscosity values were introduced. These values were compared with the data registered by the SOPF system in real time. The obtained variation diagrams for resistant torque values are shown in Figure 10, a and b.

Table 1. Viscosity values obtained in the 3D simulation, used for calculating the resistant torque values at the kneading arms

Time [s]	Viscosity Spiral arms η [Pa·s]	Torque Spiral arms CFD [N·m]	Torque Spiral arms SOPF [N·m]	Viscosity Straight arms η [Pa·s]	Torque Straight arms CFD [N·m]	Torque Straight arms SOPF [N·m]
15	2.97	129.27	99.00	6.00	261.14	55.00
30	11.19	486.90	365.00	16.67	725.55	410.00
45	13.86	603.24	455.00	17.20	748.61	820.00
60	19.70	857.47	980.00	18.30	796.49	1105.00
75	22.67	986.73	1060.00	18.70	813.90	1210.00
90	24.00	1044.47	1100.00	22.40	974.94	1315.00
105	24.75	1077.22	1150.00	23.10	1005.40	1410.00
120	25.54	1111.69	1175.00	27.70	1205.61	1630.00
135	26.14	1137.54	1188.00	34.00	1479.82	1720.00
150	26.63	1159.09	1173.00	41.52	1807.12	1760.00
165	26.33	1146.16	1158.00	40.40	1758.37	1700.00
180	25.74	1120.31	1120.00	39.60	1723.55	1650.00
195	24.55	1068.60	1072.00	37.80	1645.21	1645.21
210	24.16	1051.37	1070.00	33.40	1453.70	1550.00
225	23.72	1032.22	1063.00	29.30	1275.25	1435.00
240	23.76	1034.13	1055.00	27.30	1188.21	1324.00
255	23.76	1034.13	1035.00	26.20	1140.33	1246.00
270	23.58	1026.47	1020.00	24.30	1057.63	1232.00
285	23.36	1016.89	960.00	23.70	1031.52	1170.00
300	23.32	1014.98	945.00	22.49	978.85	1078.00

Analyzing the available data, the following observations can be formulated: increase in resistant torque is dependent on dough viscosity increase. An intensive, accelerated dough development as seen with straight arms kneading will also accelerate the degrading process of dough properties. In the studied case, the kneading time for dough developed with straight arms should be decreased with 30% when using the same recipe and manufacturing conditions.



a.Spiral arms b. Straight arms

Figure 10. Resistant torque variation for the two kneaders

Because the specific energy introduced into the dough has greater values per time unit in the case of kneading with straight arms, the resistant moment diagram also has greater values than in the other case. The difference between kneading diagrams it is also clearly shown and is due to the influence the geometry of the kneading arm has on dough development.

4. Conclusions

Approximately 70 % of the existent kneading machines used worldwide are the vertical kneading arm type with spiral geometry and significant differences can be found not only between different kneader arm geometries, but with the same kneader type from different manufacturers.

The geometry of the kneading arm is of high importance due to the influence it has over the development of dough and its rheological behavior which is continuously changing during the entire bread making process.

The results obtained in the 3D simulation and the ones obtained with the mathematical model proposed in this paper are very similar with the results obtained from experimental measurements.

Even though the spiral arm has a larger spread area than the straight arm, due to the 45° angle it makes from the vat's wall, it trains a smaller mass of dough and the shear forces are also smaller.

The geometry of the kneading arm and the kneader's overall performance has a huge influence over the development of dough and its rheological behavior. Understanding this aspect is of paramount importance, especially when acquiring new equipment which should optimally serve the manufacturing process.

The kneading process can be optimized through an accurate control of the kneading time, correlated with the optimal development of dough and which can be established with the interpretation of the mathematical model which mainly uses the geometry of the kneading arm and the vat's dimensions.

Using tridimensional simulation and mathematical modelling it is possible to establish the exact influence the geometry of the kneading arm has over the rheological, cinematic and dynamic behavior of dough during kneading process and in the later stages of manufacturing.

Using 3D simulation package ANSYS, shear forces distribution inside dough during kneading can be studied. The results obtained can be helpful for redesigning kneading equipment using 3D simulations and taking into consideration customized solutions to meet market's needs.

The proposed mathematical model offers insight into the kneading process by anticipating the rheological behavior of dough which is influenced by the geometry of the kneading arms.

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