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ANALYSIS OF DOUGH MIXING PROCESS USING CFD

У статті викладені результати дослідження процесу перемішування тіста. Приведені рівняння, що описують процес перемішування тіста, та представлені результати моделювання процесу за допомогою програмного забезпечення CFD Fluent.

Ключові слова: *процес змішування, аерація, тісто, гідродинаміка.*

Bread is an integral part of the human nourishment which is manufactured and eaten in the most countries of the world. Mixing of dough is one of the most important operations of the production process of bread from which largely depend the further development of process and quality of bread. Mixing the dough is complex process which consist of formation is a homogeneous capillary-porous mass of flour, water, yeast, salt solution and other components. Mixing process should ensure uniform mixing of all components, obtaining the appropriate properties of the dough, and create optimal conditions for the passage of further processes.

The most characteristic index of mixer is a uniformity of mixing process that is established at an appropriate time and at optimum loaded working chamber. Different types of machines are employed for mixing dough, which have different mechanical effects on the dough depending on the type of flour, recipe structure and features of the range. The concentration of individual components in the volume of mixer-chamber is leveled during of mixing.

When optimizing bread dough mixing processes it is important to consider multiple aspects such as uniform mixing of the components, compliance with the optimal times of the process, allotment product of sufficient energy, density, etc. A lot of material resources and time are being spent on study and development of new technology and mixers. It is mainly so since one of the main tasks is an experimental research which does not give a complete picture of the mixing process of the bread dough but requires a lot of material costs.

However, both groups of methods (experimental and simulation) have some similar parameters e.g. mixing duration, capacity and working chamber, etc. Due to the momentary nature of the mixing process and the physical limitation in determination of the rotating flow, exact experimental data is complicated to receive. There, CFD is an affordable analytical and computational approach to investigation. The computer technology progress and the wide improvement of CFD simulation gave the opportunity to use this approach in a wide range of food industry segments.

The case of a cylinder vessel with cylindrical fluid domains has already engrossed attention due to its frequent use in the different design of mixing components. Besides, cylindrical vessel with rotating cylindrical stirrers is one of the most popular models as a two-dimensional non-Newtonian mixing flow in experimental researches and modeling. But, the close connection of the moving elements in the complicated geometry requires the rigorous and the wide examination of turbulence models, modeling of the interface between rotating and stationary regions of the two-phase model.

In food engineering field, the mixing process has been studied as significant issue to the optimum design of mixer and optimal process parameters. In the mixing dough flow the bubble behavior has a large influence on the characteristics of the process and final product. There are many research papers which analyses this process by experiment. But accurate results on the behavior of two-phase flow have never been received due to the specifics of an interface between liquid component and air component. That is why it is important to implement numerical simulations of the behavior of the mixing process as a supplement of the experimental work. Use of numerical simulation serves better understanding of physical characteristics of these complicated phenomena with a complex dynamic behavior of two-phase flow.

Chin and Campbell have studied the aeration and rheological characteristics of bread dough produced from strong and weak flours during mixing with multiple mixer rates. Increase of the blade speed (diapason from at 40 to 70 rad/s) did not have significant impact on the gas-free dough density. However speed increase adds the hollow parts of gas which resulted in gas occlusion during the research. The research showed that gas-free dough density is increased and only then becomes constant. This is more applicable for the dough made from strong flour rather that for the one made from weak flour. Besides the research has defined the optimal mixing speed and input works which influence the rheological development of dough.

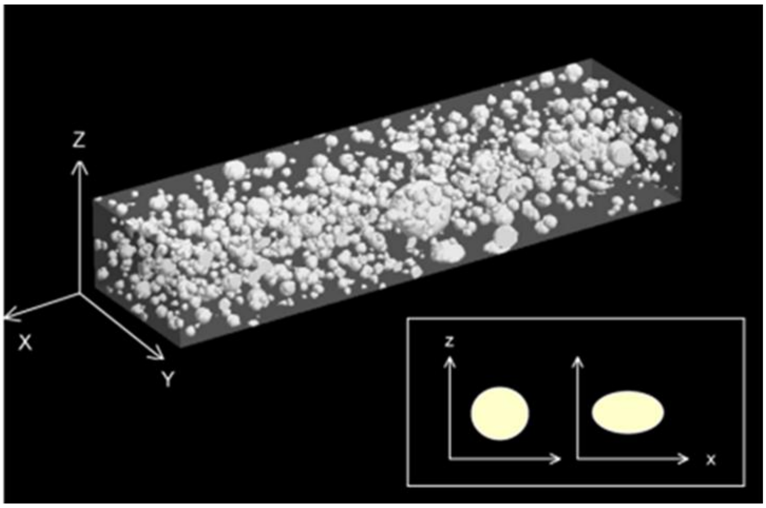

Fig. 1. Dimensional visualization of the 3D-distribution bubble size into a sample of dough

Since of the 1960s, the application of CFD new technology to all aspects of fluid dynamics was monitored, but it is applied exactly to the processing of food industry relatively recently. Xia B. and Sun D-W. have proved that reconciliation computing simulation to problems of food industry processing could help better comprehend complex physical mechanisms during food processing.

Sujatha et al. (2003) performed a research of dough kneading and the validation of surface positions which is confirming numerical modeling and experimental results for rotating flows in part-filled dough mixers. In this article, the researchers have presented a model of rotating flow in the rotating cylinder as of a part-filled dough vessel, and a stirrer is partial of the lid of the vessel. Horizontal and vertical cylinder positions with stirrer were placed in different concentric or eccentric position and various rotational speeds were studied. For the simulation both type of horizontal (2D) and vertical (3D) positions were used applying a Lagrangian–Eulerian model. Tentative photos of the surface profiles have been received thanks to use of high-speed photography and laser scatter technology. Correlation between experimental and numerical flow fields and free surface profiles received as approximately coincided. The wetting of fluid, rising at the vessel and peeling of fluid at the stirrer during mixing process were confirmed by researchers.

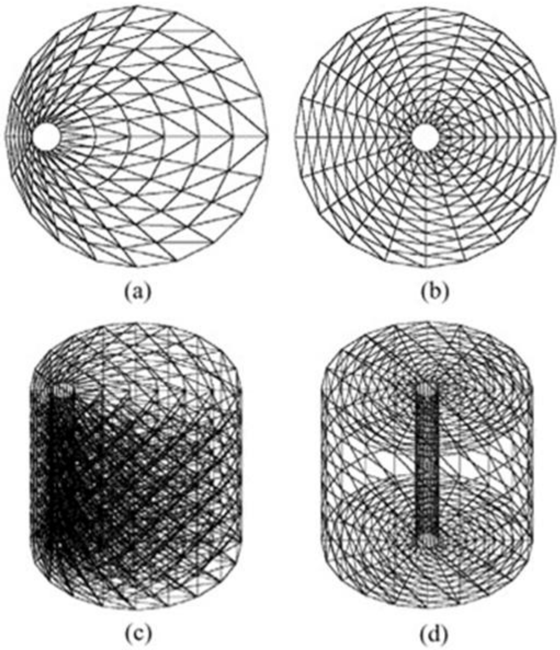

Fig. 2. Meshes: (a, b) horizontal (2D) and (c, d) vertical (3D) views

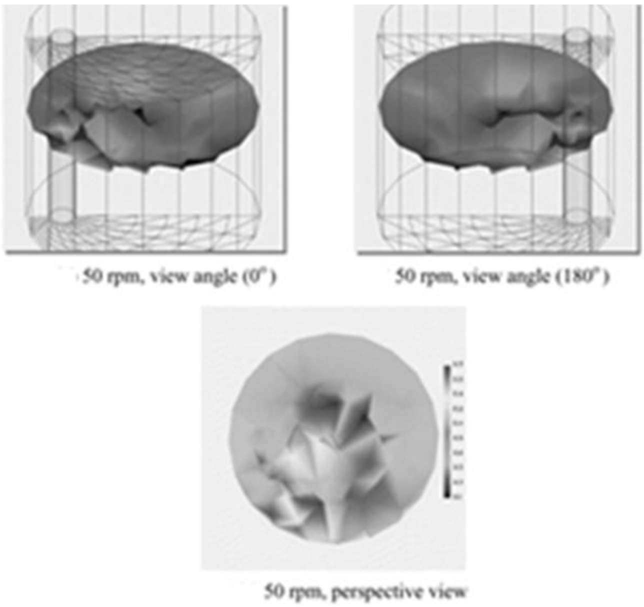

Fig. 3. Steady-state free-surface profiles, eccentric, one-stirrer geometry

Another series of studies of model simple mixer geometries was focused on the simultaneous scale-up of mixing and heat transfer in single screw extruders by several parametric 3D non-isothermal numerical simulations (Dhanasekharan) using a viscosity model of the Mackey and Ofoli. Analysis was focused on the dough as on a non-Newtonian material whose viscosity was dependent on shear rate, temperature and moisture. The computational method in this research was based on a number of simulations of flow and heat transfer with differently sized extruders (such as screw diameter, helix angle, and the clearance between the screw flights and barrel) was obtained.

The mixing process of viscoelastic flow into a single-screw continuous mixer using Finite Element Methods was studied by Connely R.K. and Kokini J.L. (2007). In this research the viscoelastic ambit was disclosed as an elastic viscous stress splitting. The increase of rpm of paddles led to increase of the parameters of all parameters with the inclusion of the shear rate. The viscoelastic problem was stabilized at higher values of the relaxation time for Newtonian fluid. The mixing process of the differential viscoelastic fluid which included velocity, pressure, and stress profiles, using FEM was achieved. Innovation of this research presupposed modelling of a viscous and viscoelastic materials (for example, dough or synthetic polymers, etc.) where is possible to tailor the viscoelastic models and use only parameters which had a strong hold over rheological characteristics of this process.

Then, Ding D. and Webster M.F. published another research paper concerning the food processing industry for the three-dimensional numerical simulation of dough mixing. Different types of mixers with multiform rotation speed of one or two stirrer are investigated. For the dough mixing with one stirrer, a central vortex arises horizontally opposite to the stirrer. In the case with two stirrers, a pair of vortex centers arisen. Same thing happened in consequence by the separating flow around each stirrer during mixing process with increasing of rotation speed. The paper presented by Ding D. and Webster M.F. are very interesting for providing understanding of how to correctly provides mixing process using inelastic fluid models and receive physically realistic simulations this process.

There were many studies related to behavior of liquid and gas flow held by numerical simulation under different conditions. In those simulations , many parameters have been investigated and showed behaviour of the two-phase flow, trajectory, changing velocity, strain rate, density of into a primarily phase with changing sizes, shape and rate of growth bubbles (air phase). The results of simulation and experimental data have a good resemblance. However, those simulations do not take into consideration changing concentration and, accordingly, density of the flow which simultaneously consists from two-phase. In order to simulate the behaviour of two-phase flow (liquid phase and bubbles phase), the VOF model will be used.

The overall goal of this research is to use 3D numerical simulations to predict the geometrical configuration and processing parameters which result in efficient mixing and to develop the methods that lead to design principles for mixers. Therefore, objective of this study is to establish the accurately physical models for simulating of the dough mixing process with changing density of flow using the User-

Defined Function (UDF) in FLUENT code. Also it is targeted at demonstration of effective mixing of complex fluid like dough into a screw-agitated vessel using CFD simulations.

The simulation of dynamic of multiphase flow has been conducted using one of the two approaches for the numerical calculation of multiphase flows - Eulerian-Eulerian method. In this approach, the two phases (air and dough) are to be examined mathematically as interpenetrating continua. So the volume of a phase cannot take up the other phases. Due to this the phasic volume fraction concept is introduced. The volumes of these fractions are appropriated to be continuous functions of time and space, and their sum is equal to 1.

The Volume of fluid model is a subspecies of the Euleran-Eulerian multiphase modelling approach, which demonstrates a particular reliability for the free-surface flow. The VOF model is a surface-tracking method which is applied for the Eulerian mesh. This model is appointed to the two or more immiscible fluids with a single set of momentum equations and the volume fraction of each of the fluids is tracked throughout the domain. Applications of the VOF model include free-surface flows and the motion of large bubbles in a liquid, the motion of liquid after a dam break, and also the steady or transient tracking of any liquid-gas interface.

In the case with two-phase flow, which is mixing in the vessel: the liquid component has volume fraction α_1 and gas component has volume fraction α_g. There lationship between phases followed as:

$$\alpha_l + \alpha_g = 1. \qquad (1)$$

In turbulence model for mixture (for two phases) the density and velocity will be Favre-averaged:

$$\rho = \alpha_l \rho_l + \alpha_g \rho_g, \qquad (2)$$

$$\rho V = \alpha_l \rho_l V_l + \alpha_g \rho_g V_g. \qquad (3)$$

For the turbulence kinetic energy k, the transport equation defined as:

$$\frac{\partial k}{\partial t} + \rho V \times \nabla k - \nabla[\alpha \mu_t \nabla k] = \mu_t \sum_{i,j} \frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \rho\varepsilon, \qquad (4)$$

and the dissipation rate introduced as:

$$\rho \frac{\partial \varepsilon}{\partial t} + (\rho V)\nabla\varepsilon - \nabla[\alpha \mu_t \nabla \varepsilon] = -pS + C_1 V_1 \frac{\varepsilon}{k} \sum_{i,j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - C_2 \rho \frac{\varepsilon^2}{k}. \qquad (5)$$

The μ_t turbulent viscosity could be introduced as:

$$\mu_t = \rho V_{mol}\left[1 + \left(\frac{C_\mu}{V_{mol}}\right)^{1/2} \frac{k}{\varepsilon^{1/2}}\right]^2. \qquad (6)$$

Where C_μ, C_1, C_2, β, α are constants.

The gas-liquid phase flow was investigated in the cylindrical vessel with four baffle and rotating screw. In this work, it is assumed that pure air gets into vessel through top wall of the vessel, which is modeled as a pressure-outlet. Other sides of vessel are modeled as solid walls. The vessel is filled with dough up to level of 0,075 m and the remaining space contains air. There are not imposed slip boundary conditions to the all walls and they are calculation as a via standard wall functions. The top of liquid surface is considered as a flat, and air bubbles can be distributed by the screw along of the all vessel. Through the technique of the moving region, the fluid attached to the screw volume has been set at 50 and 100 rpm, which corresponds to the screw rotational speed.

The air distribution in the dough depends on multiple parameters, such as: vessel configuration, screw speed and gas-liquid flow rate. In this case, it is not important to calculate bubbles size, but only to analyses concentration of air component, sing a multi-phase model for mixture. Fluid properties have been set as follows: dough as primary property and air as a secondary phase. The density of dough changes with time by the user-defined function. The RNK k-e model for mixture has been chosen due to the fact that this model has the stability mattered. RNK k-e model switch on, because it is applicable for the swirling flows. The standard wall function has been shown as preferred since they allowed the simulation running quicker than in cases other near-wall treatments.

Due to the dynamic field of the flow and the mesh size, in the condition of time-dependent analysis the decision on the recommended time step of simulation has been made. The time step used in the simulation is 0,025 sec and 30 max iterations per time step.

The flow structures in a case of two-phase flow in mixer are known to be highly complex associated with time-dependent, three-dimensional phenomena enveloping a wide range of temporal and spatial variables. The effect of changing density, in the case of two-phase flow, during mixing process was investigated using a simple model of an industrial mixer, and the conclusions that could be done from this work are that the density is changing under the penetration ability of air due to the influence of rotating impeller, while the dough density is reducing. It was found that to the rate of reducing of density of dough in general is influenced by the design of a mixer and parameters of process, such as duration of mixing, the screw speed, the disposition of baffles and rotating screw.

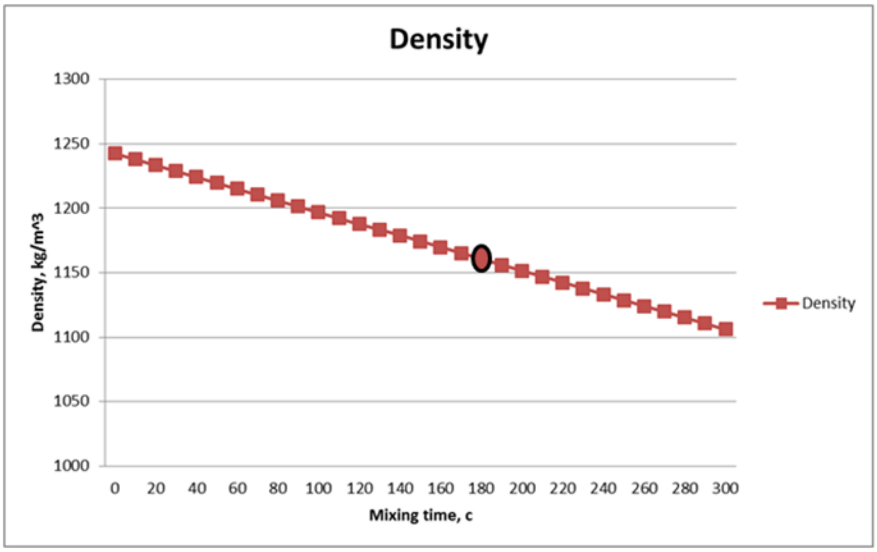

Fig. 4. Changing dough density during simulation (optimal density 1,16 g/cm^3±0,0021g/cm^3 at 184 s)

Also, it was observed that the speed of rotating screw has effect on speed of air capturing and the equable distribution along the vessel; and as a result the higher speed was facilitated to the more rapid penetration and equable distribution of air and the tangibly reduced duration of mixing. The simulation was performed using the FLUENT CFD package. The optimal mixing time for the wheat dough was found.

Conclusions

This study provided better understanding of the two-phase flows within simple mixer geometry. In this case the experimental data for dough mixing process which includes two phases is difficult to obtain, the results of the CFD simulations are important and valuable for any further investigation of the mixing process of a complex fluid. Therefore, the widely used commercial CFD software predicts accurately the behaviour of a flow in the fixed geometry. Finally, the overall magnitude of the flow behaviour and changing density are agreed with experimental information that is available in the literature, and were realized by the Fluent via User Defined Functions.

The work done in this investigation mainly focused on obtaining the velocity and density profiles for the different rotating speed of impeller, and also performing the parametric analysis of flow parameters in a specific geometry of vessel.

1. Chiotellis E. and Campbell G.M. (2003) Proving of bread dough I Modelling the Evolution of the Bubble Size Distribution. Institution of Chemical Engineers Trans IChemE, Vol 81, Part C.
2. Connelly R.K. and Kokini J.L. (2007) Examination of the mixing ability of single and twin screw mixers using 2D finite element method simulation with particle tracking. Journal of Food Engineering, No 79, pp. 956-969.
3. Dobraszczyk B.J. and Morgenstern M.P. (2003) Review: rheology and the bread making process. In Journal of Cereal Science, Vol. 38, pp. 229-245.
4. Sujatha K.S., Webstera M.F., Bindingb D.M. and Couch M.A. (2003) Modelling and experimental studies of rotating flows in part-filled vessels: wetting and peeling. Journal of Food Engineering, Vol. 57, Issue 1, pp. 67-79.
5. Xia B., Sun D-W. (2002) Applications of computational fluid dynamics (CFD) in the food industry: a review. Comput. Electron. Agric. 34, pp. 5-24.