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THE MIXING ANALYSIS OF NON-NEWTONIAN FLUIDS SUPPORTED BY CFD NUMERICAL SIMULATION

Summary

The article describes the problem of mixing process analysis of non-Newtonian fluids supported by CFD numerical simulation. To introduce the analysis method of the mixing process a series of numerical experiments was carried out exemplified by vessel equipped with two types of agitator with rotary coil. There was shown velocity magnitude distribution in two perpendicular cutting planes and velocity profiles for both constructional agitator solutions. Moreover, it was provided comparative analysis, which showed impact of viscosity and rotation velocity of agitator on nature of the mixing process.
Key words*: non-Newtonian fluids, mixing process, CFD simulation*

ANALIZA PROCESU MIESZANIA CIECZY NIENEWTONOWSKICH WSPOMAGANA SYMULACJĄ NUMERYCZNĄ CFD

Streszczenie

W artykule przedstawiono problematykę analizy procesu mieszania cieczy nienewtonowskich z wykorzystaniem symulacji numerycznej CFD. Celem prezentacji sposobu analizy zjawisk towarzyszących mieszaniu przeprowadzono serię eksperymentów numerycznych na przykładzie zbiornika wyposażonego w dwa warianty mieszadła wężownicowego. Przedstawiono mapy prędkości chwilowych mieszanej cieczy w wybranych płaszczyznach oraz profile prędkości dla obu rozwiązań konstrukcyjnych mieszadeł. Ponadto, dokonano analizy porównawczej obrazującej wpływ lepkości cieczy oraz prędkości obrotowej zespołu mieszającego na charakter procesu mieszania.
Słowa kluczowe*: ciecze nienewtonowskie, proces mieszania, analiza CFD*

1. Introduction

Mixing process is one of the main methods of intensification of heat and mass exchange process. It is also used to accelerate the physical and chemical reactions.

The range of industrial application of mixing process is very wide, especially in food industry [1]. In general mixing of liquid foodstuff is executed in vessels equipped with agitators. According to [3] a lot of foodstuff fluids is non-Newtonian. The selection of geometric parameters of agitator is usually intuitive and is based on experience of a manufacturer. The modern science fulfilling expectations of the industry provides a range of engineering tools that are invaluable help for designers of food mixers. The software for Computation Fluid Dynamics (CFD) is one of the such tools. The CFD software is used to develop sophisticated mathematical models that enable the realization of numerical computation, to solve and analyze problems related to the fluid flow. Thanks to CFD a mixing process study of the new agitator may be carried out and this- without building a physical prototype.

2. Approach and limitation

The design process requires to set appropriate geometric features of every single part of agitator assembly. The key condition is to ensure high performance mixing process, while reducing energy consumption of agitator drive.

The CFD simulation is very useful tool to make design process easier and more accurate. The foundation of CFD is based on three basic fluid dynamic principles [2]: conservation of mass (1), conservation of momentum (2) and conservation of energy (3).

$$\frac{\partial \rho}{\partial t} + \rho \nabla u = 0 \quad (1)$$

$$\rho\, \partial u / \partial t = \rho F - \nabla p + (\nabla^{\uparrow} 2\, u \quad (2)$$

$$\rho \frac{u^2}{2} + p + \gamma z = const. \quad (3)$$

where:
ν - kinematic viscosity,
u - fluid velocity,
p - pressure,
ρ - fluid density,
∇ - divergence,
F - external force,
γ - specific weight.

The agitator design approach is based on comparative analysis of simulation results, that was made for different shapes of agitator. As a general rule the boundary conditions applied to simulation should be the same for every case. The final stage of analysis concerns comparison of the results and type the best construction solution of agitator.

The study objects included two similar agitators with rotary heating coil and scrapers. One of this agitators was additionally equipped with two mixing ribs (fig. 1).

The simulation was provided by XFlow software. The key features of XFlow consist in meshless approach to CFD, particle – based kinetic solver and adaptive wake refinement. The particle-based kinetic algorithm resolves the Boltzmann and compressible Navier-Stokes equations. This method advects discrete markers at the bulk of the flow and detects an interface whenever the fluid particles of different type are neighbouring each other (Lagrange method) [6].

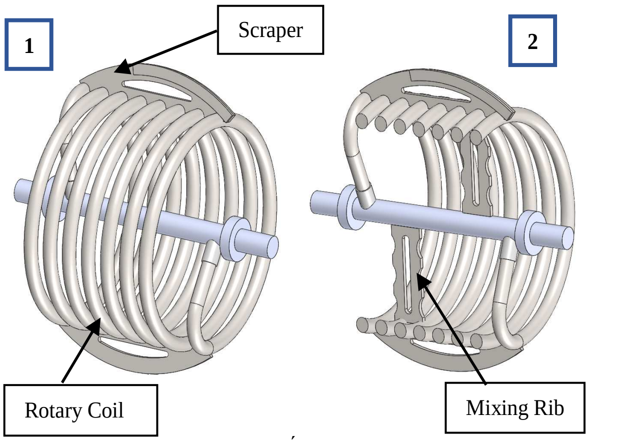

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Fig. 1. The computational model of agitator: 1 – basic, 2 – with mixing ribs
Rys. 1. Model obliczeniowy mieszadła: 1 – wersja podstawowa, 2 – wersja z żebrami

Firstly, it was set appropriate boundary conditions, which mean implementation of fluid parameters, agitator velocity, turbulence model, reference area and velocity etc. In the present case free surface mixing process of fruit jam, which is non-Newtonian fluid was analyzed (tab. 1). The velocity of agitator was 17 rpm. It is the standard parameter in such application. Then it was generated domain structure, that is equivalent to mesh in mesh-methods (fig. 2).

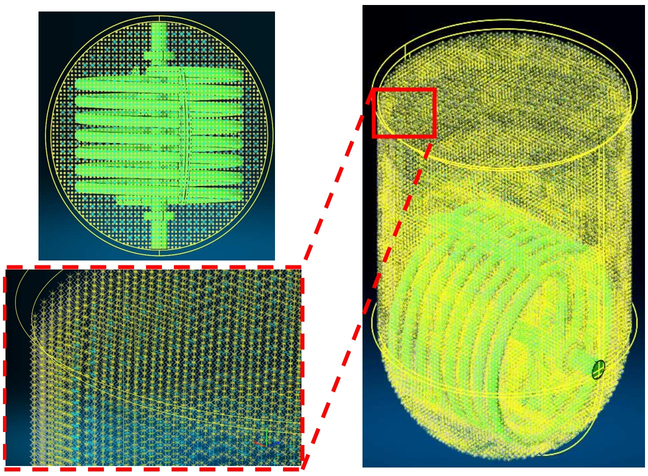

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Fig. 2. Domain structure
Rys. 2. Struktura domeny

Markers are one of the representation modes. They are advected with the flow and introduced at the interface between phases (fig. 3).

The results of simulation was presented in form of maps of fluid velocity magnitude in two perpendicular cutting planes (fig. 4).

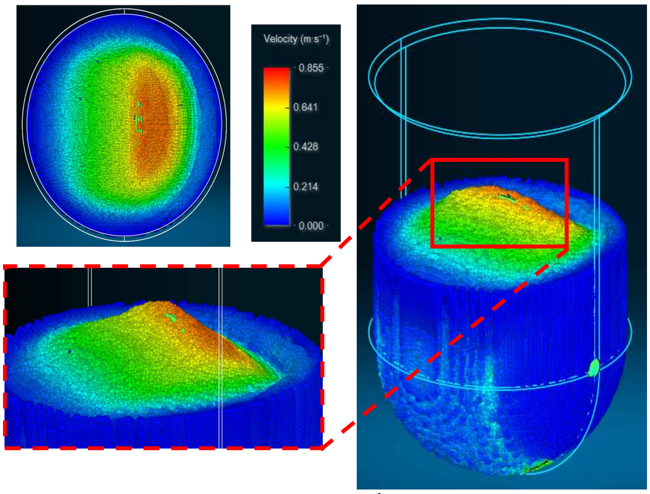

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Fig. 3. Markers with spheres representation
Rys. 3. Markery pomiarowe reprezentowane przez obiekty sferyczne

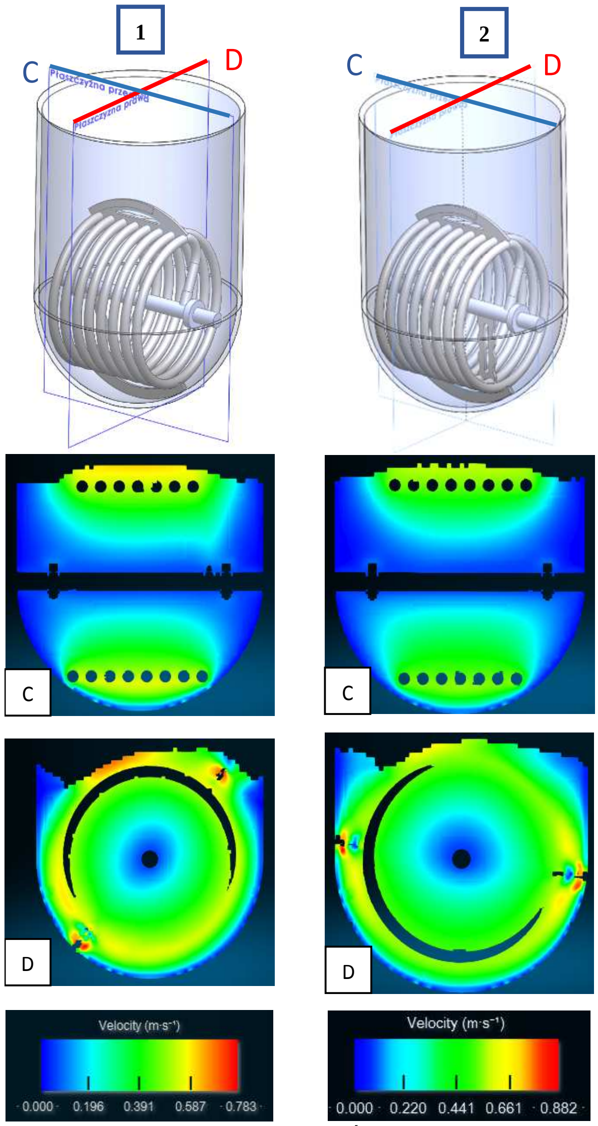

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Fig. 4. Velocity magnitude distribution in two perpendicular cutting planes: 1 – basic agitator, 2 – agitator with mixing ribs
Rys. 4. Rozkład prędkości płynu dla dwóch prostopadłych płaszczyzn przekroju: 1 – wersja podstawowa mieszadła, 2 – wersja z żebrami

In both cases of agitators the velocity distribution is very regular. There are some visible regions of flow stagnation. Nevertheless, the movement of scrapers generates periodically the flow in this area. The impact of mixing ribs can be observed on velocity profiles (fig. 5).

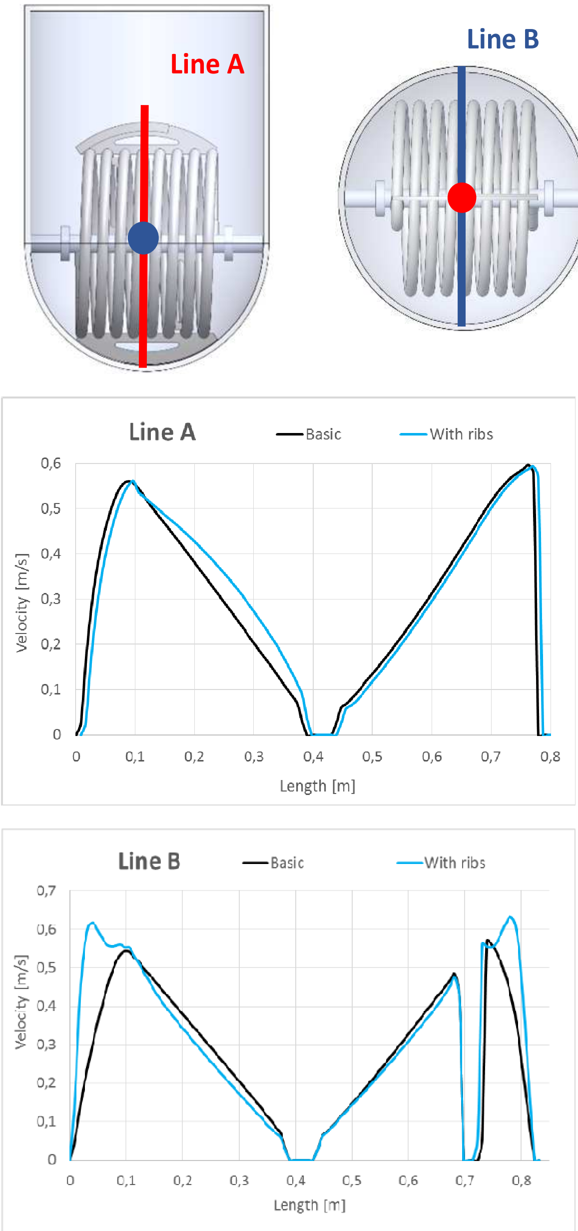

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Fig. 5. Velocity profiles collected from two perpendicular measurement lines
Rys. 5. Profil prędkości zarejestrowany dla dwóch prostopadłych linii pomiarowych

In the middle range on the line A a significant velocity increase is visible. This effect is characterized by asymmetry, because the velocity profile was registered for one agitator position and it will follow the agitator motion. The range of zero value means that measurement lines cross the agitator model.

3. Impact of fluid viscosity

The impact of fluid viscosity is very significant. To show a big difference between mixing process of two non-Newtonian fluids it was performed another comprehensive analysis. The agitator shape and other simulation conditions were the same, but it was implemented two fluids, which differed by rheological properties (tab. 1).

Tab. 1. The rheological properties of analyzed fluids [4, 5]
Tab. 1. Właściwości reologiczne analizowanych płynów [4, 5]

	Jam	**Tomato paste**
Density [kg/m^3]	1301	1130
Viscosity model	Hershel-Bulkley	Hershel-Bulkley
Consistency index (k) [Pa·s^n]	2,02	24
Powerlaw index (n) [-]	0,71	0,23
Yield stress threshold (τ_O) [Pa]	99,14	38
Yielding viscosity (μ_O) [Pa·s]	55	300

The results of this analysis are shown on fig. 6.

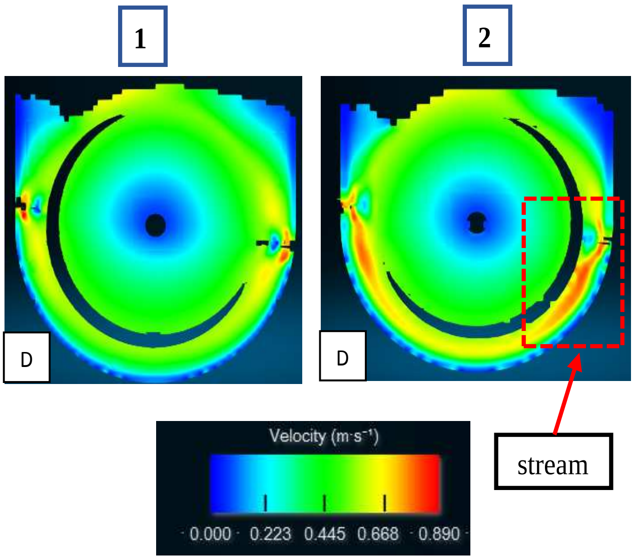

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Fig. 6. Velocity magnitude distribution: 1 - jam, 2 - tomato paste
Rys. 6. Mapa prędkości mieszanego płynu: 1 - dżem, 2 - przecier pomidorowy

The velocity maps are relatively the same, excluding stream generated by scrapers in case of tomato paste mixing process. This is due to the fact, that consistence index of tomato paste is 12 times bigger than jam' s one.

On the other hand, the mixing of tomato paste is related to torque increase. Fig. 7 shows the torque curve as a function of simulation time. In steady state the torque in case of mixing tomato paste is higher by approximately 50 Nm. Moreover, the amplitude of torque in case of mixing jam is approximately 15 Nm (excluding start-up phase), but in case of mixing tomato paste the torque fluctuates with amplitude of 40 Nm. This means, that selection of electric motor should be done taking into account the load variability. Besides that, the collected load data will be used to determined boundary condition applied to strength analysis of developed agitator.

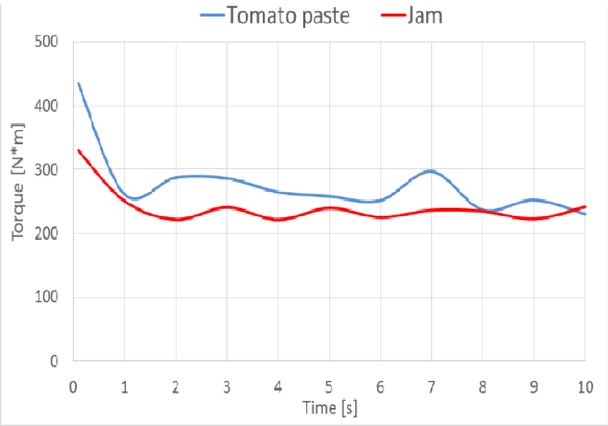

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Fig. 7. Torque curve as a function of time for two analyzed liquids
Rys. 7. Przebieg momentu w funkcji czasu dla dwóch analizowanych cieczy

4. Impact of agitator speed

The agitator speed is another important parameter of mixing process. As already mentioned, the standard value of agitator speed equals about 17 rpm. There was carried out another study, that showed the impact of agitator speed on the mixing process parameters. It was included two agitator speeds i.e. 17 rpm and 34 rpm. Fig. 8 shows the results of analysis.

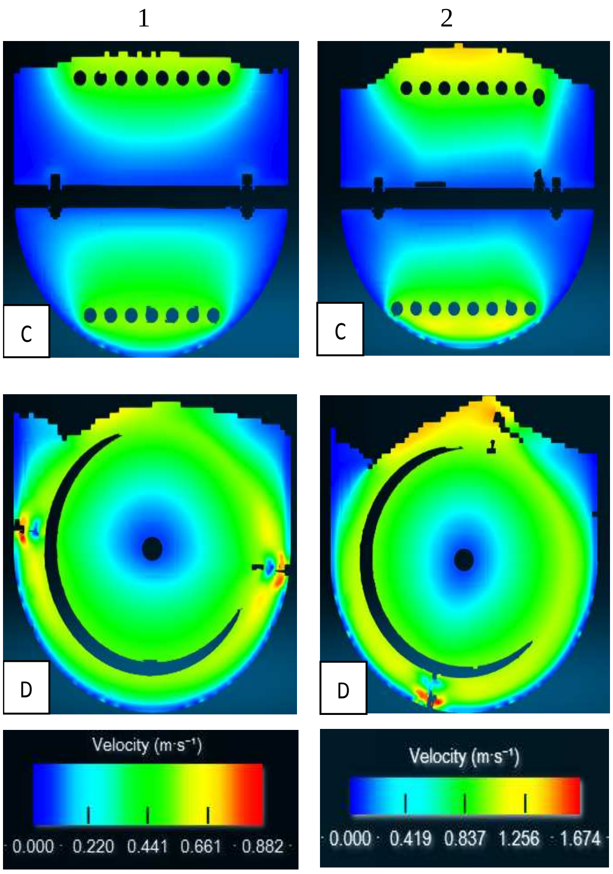

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Fig. 8. Velocity magnitude distribution: 1 - 17 rpm, 2 - 34 rpm
Rys. 8. Mapy prędkości mieszanej cieczy 1-17 obr·min^{-1}, 2-34 obr·min^{-1}

The fluid velocities are obviously different, but the maps without including the values are very similar.

To properly perform long term mixing process, especially connected with heat exchange, it is necessary to avoid flow stagnation.

The nominal velocity value of fluid is secondary issue. Fig. 9 shows the torque curve as a function of mixing time for two different agitator speeds.

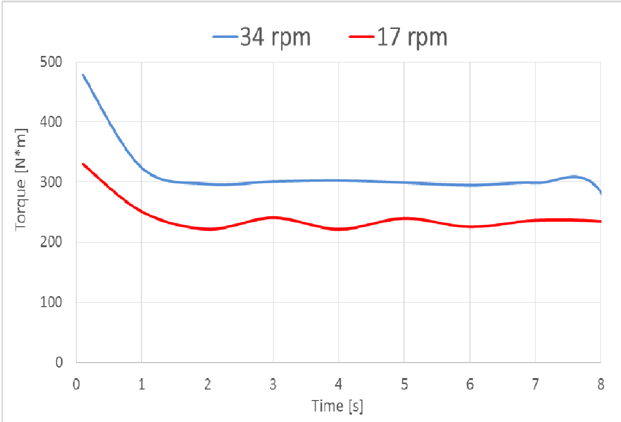

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Fig. 9. Torque curve as a function of time for two agitator speeds
Rys. 9. Przebieg momentu w funkcji czasu dla dwóch prędkości mieszadła

Doubling the agitator speed results in an increase in torque in steady state by approx. 70 Nm, while the torque in start-up phase is higher by approximately 150 Nm. The increase in fluid velocity in executed mixing process is a desirable effect, however, closely related to an increase in energy consumption, especially in the context of long-term operation.

5. Summary and conclusions

The study shows that CFD numerical simulation can be very useful engineering tool, which can support design process of all machines types related to fluid dynamics. Among the applications the agitators, which are very widely used in vessels can be mentioned. The analyzed object included two simple types of agitator in form of rotary coil with scrapers. One of it was equipped with mixing ribs. It was designated the fluid velocity field, which was presented by maps obtained through cutting planes. Moreover, it was set the velocity profiles, that proved to be very useful to observe the effect of mixing ribs.

Finally, there were carried out two another studies, that show the impact of fluid rheological parameters and agitator speed on mixing process. The collected data are a valuable guide, which indicates the desirable design features of new agitator.

6. References

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