Effect of tank geometry on flow characteristics and energy consumption in mechanical mixing

Anna Młynarczykowska[1*], *Marek* Jaszczur[2]

[1]AGH University of Krakow, Faculty of Civil Engineering and Resource Management, Mickiewicza 30, 30-059 Kraków, Poland
[2]AGH University of Krakow, Faculty of Energy and Fuels, Mickiewicza 30, 30-059 Kraków, Poland

Abstract. Mixing, understood as a process in which the mutual movement of particles within a given medium leads to homogeneity, is one of the most common processes used across various technologies and industries. It is used in pharmaceuticals, petrochemicals, metallurgy, mineral processing, the food industry and more. Substances in different states of matter and with varying physical or chemical properties can undergo mixing. Mixing may occur in single-phase, two-phase, or multiphase systems. The method used depends on the desired outcome and the required time scale. Additionally, the following factors must be considered: the geometry of the mixing tank, the viscosity of the mixed phases, temperature, fluid density, and the shape of the impeller. These parameters determine mixing efficiency and energy consumption. The optimal design of impeller geometry for tanks with simple and easy-to-manufacture shapes (e.g. cylindrical or cubic) continues to attract the interest of researchers. An alternative approach in modelling, particularly in turbulent flows, involves modifying the tank geometry by introducing baffles to stabilize the flow. The main objectives of this research is to characterise fluid flow and evaluate the energy consumption of mixing in a mechanically agitated cylindrical tank, both with and without baffles. The effect of baffle size on fluid flow and mixing, as well as the required agitator power, was also investigated. Mixing efficiency was evaluated using flow velocity from Particle Image Velocimetry and Computational Fluid Dynamics simulations, while the required power was determined form precise torque measurements. The experiments were conducted under variable hydrodynamic conditions for several impeller design. Results indicate that the presence of baffles affects the fluid flow characteristics inside the tank by altering the pumping efficiency (Q_r) and the power number (Np), as well as mixing efficiency E

1 Introduction

Mechanical mixing is widely employed in chemical processes, the food industry, pharmaceuticals, wastewater treatment, and mineral processing, among others. It is critical for specific operation such as dispersing gases into liquids, producing suspensions and freely settling mixtures, and preventing sediment aggregation or undesired chemical reactions [1, 2].

The selection of impeller type and tank geometry depends on the type of substances being mixed and the desired processes outcome.

The technological aspect concerns the preparation of mixtures and the enhancement of process performance while ensuring the correct physicochemical transformations. The scientific aspect encompasses development of mathematical and physical models and process optimization based on numerical simulations and with subsequent experimental validation. The methodological approach facilitates the design and scale-up of new mixing systems. Including tanks and impellers, and helps to mitigate uncertainties between laboratory and industrial scales.

The key element of mechanical mixers is the agitator, whose geometry and rotational speed generate a characteristic velocity fields: radial, axial, or mixed. Typical agitator types include turbines, propellers , discs, pitched-blade-turbines, frame , etc. Their use depends primarily on the viscosity and rheological behaviour of the mixed fluids. The most commonly used a high-speed turbine, propellers or disc type bladed agitators are commonly used, because they effectively mix single-phase liquids and gas-liquids mixtures for viscosities approximately in the range from 1 to about 10^4 mPa*s. These rotors generated predominantly radial or radial-axial flow patterns.

Intense mixing at high rotational speeds can induce undesirable aeration of the fluid due to the hopper formation and turbulence, in mixers often the baffles are introduced(typically two to four), which separate stirring areas.

Many researchers describing the mechanical mixing process report good agreement between predicted and experimentally measured mixing efficiency at a given time for a wide range of impeller shapes and diameters

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* Corresponding author: mindziu@agh.edu.pl

[3,4]. For the above-mentioned rotor types [5], blade number, geometry , and positioning of the blades [6] substantially influence power, consumption , mixing quality and process efficiency.

Suzukawa et al. [7] used Computational Fluid Dynamics (CFD) together with Laser Doppler Velocimetry (LDV), to investigate the effect of blade inclination (45°, 60°, 75°, and 90°,) for a four-bladed turbine on the structure of the rolling and trailing vortex in the mixer and the energy consumption of the mixing process. The flow pattern produced by a flat paddle impeller (alfa= 90°) produces no trailing vortex, but forms a pair of roll vortices, whereas obliquely pitched blades promote formation of a single trailing vortex near the blade tip. Similarly Nagata [8] in experimental studies, showed that the power number for a two-blade pitched-blade rotor (PBT2) is reduced when blades are skewed.

It has been shown that an optimal and practically sufficient number of turbine blades is about six, because a larger number of blades in the impeller only slightly increasing the power mixing and has negligible improvements in mixing efficiency.

Godlewska and Karcz [9] through experimental research carried out for low-viscosity fluids demonstrated that the value of the power number decreases as a baffle length is reduced for a fixed blade inclination and for six blade pitched blade turbine (PBT), for a fixed baffle length, the power number increases with the increase blade pitch angle.

Jaszczur et al. [4] analyzed the flow pattern of water and glycerine in a mechanically stirred cylindrical tank without baffles comparing a Jet1 rotor with a Rushton turbine. In both cases blades were oriented perpendicular to the shaft. Based on the analysis of velocities vectors distributions and the normalized pumping number, the authors estimated energy consumption and mixing efficiency. Their experimental and numerical results indicate that the power number for the Jet-1 rotor is approximately 6-10 times lower than for the Rushton turbine implying substantially lower energy demand at the same rotational speed. At the same time, mixing efficiency, which depends indirectly on the Reynolds number, can be significantly higher for the tested new rotor than for the reference Rushton turbine.

Historically, optimization of tank and impeller geometry relied predominantly on experimental testing. Currently, advanced computational methods and mathematical models are routinely used as an initial design tool. This allows prediction of the mixing hydrodynamics for complex systems and reducing the cost and duration of experimental campaigns. Nevertheless, experimental validation remains essential to confirm numerical predictions and provide data for model refinement.

Accordingly, this study presents a combined numerical and experimental investigation **flow pattern**, **energy consumption** and **mixing efficiency** for an innovative jet impeller **(Jet-1)** in **comparison Ruston turbine** in cylindrical tanks with varying internal geometries.

The results are compared with selected literature data.

The main objective was to maximise **mixing process effectiveness while minimizing energy consumption.**

In order to achieve this, advanced Computational Fluid Dynamics (CFD) simulations coupled with Particle Image Velocimetry (PIV) measurements were employed.

Mixing efficacy was quantified form measured torque under variations of impeller geometry, rotational speed and fluid viscosity. Flow patterns were characterised using velocity fields for a selected cross-sections from Particle Image Velocimetry measurement.

Based on the experimental data the power number N_p, normalized pumping capacity K_c and mixing efficiency E were calculated - three key parameters that characterise mechanical mixing performance.

2 Experimental set-up and methodology

The experimental setup consisted of a cylindrical tank and a mechanically driven agitator powered by an electric motor with continuous speed control (Figure 1). The investigated tank had smooth walls with the possibility of installing up to four baffles of various lengths and with adjustable distances from the vessel bottom. The dimensions of the tank, baffles and impellers dimensions are presented in Table 1. The thickness of the baffles and impellers was 2 mm. The distance between the impeller and the bottom of the tank h was fixed and set at 1/3·H. As working fluids deionized water (ρ = 998.2 kg/m3, μ = 0.001004 kg/(m·s) at 20°C) and 100% glycerine (ρ=1261.1 kg/m^3, μ=1.4101 kg/(m·s) at 20°C) were used.

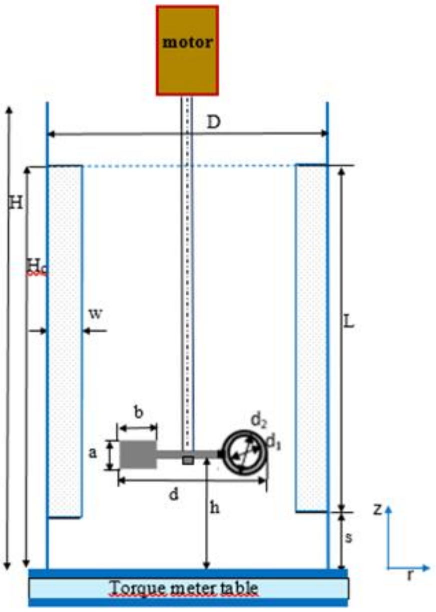

Fig. 1 Schematic diagram of the turbine and stirred tank

As impeller six-bladed Rushton turbine and a three-arm impeller with bucket blades (Jet-1) were used. The geometrical parameters satisfied the following relationships: $H = D$, $d = 1/3D$, $h = 1/3D$, w = 1/10D, $s + L = H$. The upper edges of the baffles was always located at the level of the liquid free surface.

Table 1. Dimensions of the stirred vessels

Parameter	Symbol	Value, mm
Height of the tank/fluid	H_c / H	300 / 170
Diameter of the tank	D	170
Diameter of the impeller	d	85/57
Impeller distance from tank bottom	h	57
Height, width for RT blades	a / b	12/15
Length forJet-1 bucket's	l	40
Diameter of the bucket's	d_1 / d_2	15 / 18
distance between lower edge of the baffle and bottom of the vessel	s	0-170
Length of the baffle	L	170-0
Width of the baffle	w	20

Flow fields were obtained using Computational Fluid Dynamics (detailed model described in [2, 4] and Particle Image Velocimetry measurements, while the energy demand was measured using a precise torque meter FSA-2 (AXIS, max 2 N·m) with an accuracy of 0.001 (N·m) and a sampling frequency of 1000 Hz. The rotational speed of the impeller was varied in the range from 60 to 600 rpm.

The experimental measurement procedure included the following steps:

1. Torque measurement: the rotor was mounted on the shaft and installing the mixer on the FSA-2 torque measuring device.
2. PIV measurements: instantaneous velocities in the vertical plane were recorded using the Particle Image Velocimetry for a cylindrical tank placed inside a square water shield. The stirred vessel was illuminated with a double-pulse Nd:YAG laser with the energy of about 30 mJ per pulse and a vertical laser sheet was located through the centre of the tank. In this configuration, single CCD camera - La Vision with a resolution of 2048x2048 pixels was used [10] to record particle images. PIV measurements were performed for various rotor speed and the configurations with and without baffles within the tank.
3. Post-processing and nondimensional parameter calculation: based on experimental results, non-dimensional power number (N_p), the normalized pumping capacity ($K_c=Q_r/Nd^3$) and the mixing efficiency (E) were determined. These the key parameters were calculated using the following formulas:

$$Re = \frac{nd^2\rho}{\mu} \tag{1}$$

$$N_p = \frac{P}{\rho n^3 d^5} \tag{2}$$

where: ρ - density (kg/m^3), μ- viscosity (kg/m·s), n - agitator speed (1/s) , d - impeller rotor maximum diameter (m), P – power (W) required to rotate the impeller with the specified rotational speed. Power was calculated from torque measurement as follows :

$$P = 2\pi \cdot n \cdot \tau \tag{3}$$

where τ is the torque (N·m).

The third important parameter that indicates the relationship between pumping capacity and energy consumption is mixing efficiency (E), described by the equation:

$$E = \frac{K_c}{Np} 100\% \tag{4}$$

where Q_r is the radial pumping capacity which dependents on the Reynolds number. The radial pumping capacity determines the stream of fluid flow through a cylindrical surface with a specified radius *r* or through the horizontal surface at specified heights *z*.

In this study, owning the chosen impeller geometry and measurement plane the radial pumping capacity was evaluated at radius *r*= 35 mm, by using the relationship:

$$Q_r = \int_{z_1}^{z_2} |u_r| dS \tag{5}$$

where the height is: z_1=0 and z_2=0.17 m

The global flow characteristic for a given mixer geometry can be characterized by this parameter, but normalizing its value to the rotational speed and impeller diameter enables comparison of mixing efficiency and energy consumption for different impellers. this normalization is the most appropriate method, as no single universal criterion that fully characterizes mixing intensity has yet been found for all mixer types.

3 Results and discussion

3.1 Torque measurements and mixing process performance

The first step this study was to evaluate the influence of impeller geometry and fluid viscosity on the resistance during the mixer operation by measuring torque. Figure 2 shows the measured torque as a function of rotational speed for tested impellers in the cylindrical tank without baffles, using glycerine as the working fluid. The high viscosity of glycerine produces substantially larger torque values overall. This effect is particularly pronounced for the Jet-1 rotor, which is attributable to its bucked-shaped blades and the resulting flow pattern. The experimental results were consistent with CFD simulations.

Figure 3 summarises the determined torque values for the low-viscosity fluid (water) for the Ruston turbine and compares them with available literature data [11]

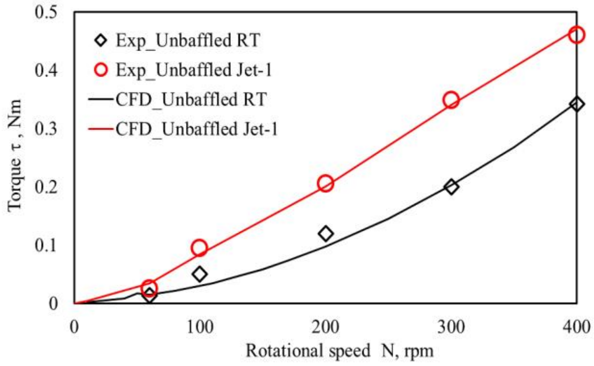

Fig. 2. Torque as a function of rotational speed for Jet-1 and Rushton turbine operating in glycerine.

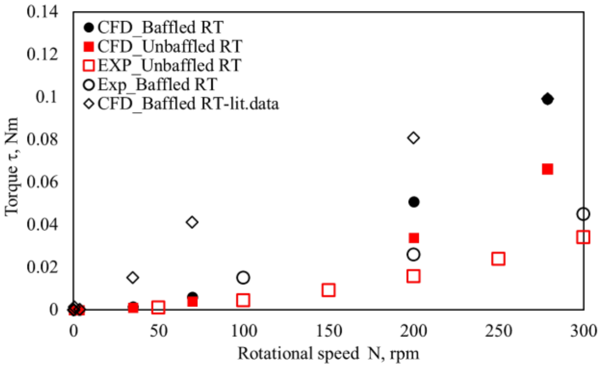

Fig. 3. Torque as a function of rotational speed forRuston turbine operating in water.

Based on experimental results, including PIV, the nondimensional parameters normalized pumping capacity K_c and power number N_p, were calculated. Figures 4 and Figures 5 present these parameters as function of the Reynolds number for the tested impellers and reference geometries from the literature, such as the pitched blade turbines with the four or six blades - PBT6 [9], PBT4 [7], with perpendicularly position of blades. Presenting the results in dimensionless form allows direct comparison between different impeller designs and operating conditions.

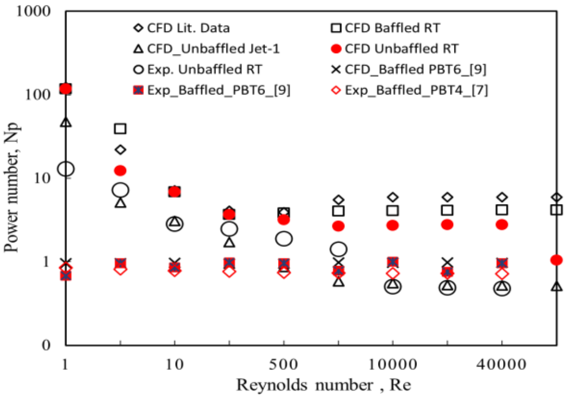

Fig.4. Power number N_p for Rushton turbine and for difference impeller design operating in a wide viscosity range.

Based on the results in Figure 4, it can be indicated that the lowest energy demand during mixing is observed for the paddle impellers (PBT6 and PBT4) placed in the four-baffle tank. Power numbers below 5 were recorded for these impellers, that confirms the low energy consumption during mixing. It is observed for these impellers regardless of the Reynolds number. It should be noted that the limit values of Reynolds number are as follows: 1.2×10^5 for PBT4 and the corresponding value of Np equal to 4.72 [7] and for PBT6 to be 4.45 for Re $=10^5$ [9]. Similarly, stable power number values (average Np. = 2.73 for Re=10^4-10^5) were achieved by the Rushton turbine regardless of the presence of baffles.

It should be noted, that the power number of the typical Rushton turbine (the angle of blades is 90°) for an agitated tank without of baffles it is higher rather than for different angles of blades. It's worth noting that the characteristic feature that describes each type of impeller is its fluid pumping capacity (Qr_r, expressed by the dimensionless normalized pumping efficiency K_p. This parameter allows for comparing the performance of the mixers.

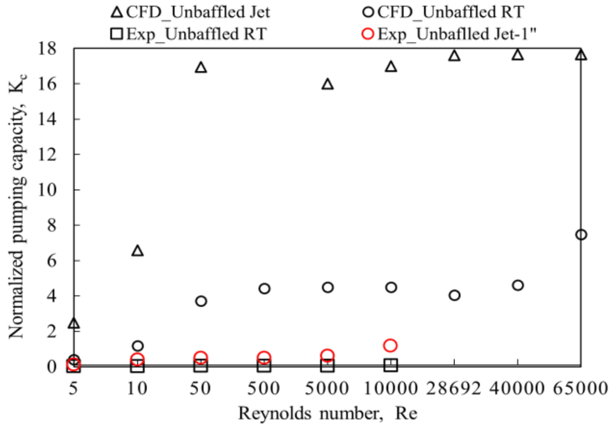

Fig. 5. Normalized pumping capacity for difference impeller design operating in a wide viscosity range.

Figure 5 shows a comparison of the normalized pumping efficiency (K_p) values for the turbine with bucket (Jet-1) and cubic (Jet) blades. The significantly higher values obtained from CFD modeling for the Jet impeller suggest better hydraulic pumping conditions for this turbine. This is consistent with the highest mixing efficiency (20%) obtained for the limiting Reynolds number *Re*=500 (see Figure 6). The Jet-1 impeller and the Rushton turbine have comparable pumping efficiency determined experimentally. Numerical calculations for the Ruston turbine predict six times higher K_p values (approx. 4 for *Re*>500), while the theoretical normalized pumping efficiency K_p should be around 0.72 for it. This results was obtained for experimental measurements for high fluid viscosity (see Figure 5).

The mixing system efficiency *(E*) was calculated based on flow patterns and energy consumption (see section 3.1). The mixing efficiency was assessed for the tested impellers under the conditions of the mixer operating inside a tank without baffles. The results show Figure 6.

A detailed analysis of the power number N_{p}., mean axial normalized pumping capacity K_c for Jet-1 impeller and Ruston turbine in function of Reynolds number with varying impeller distances from tank bottom was presented in the paper [4].

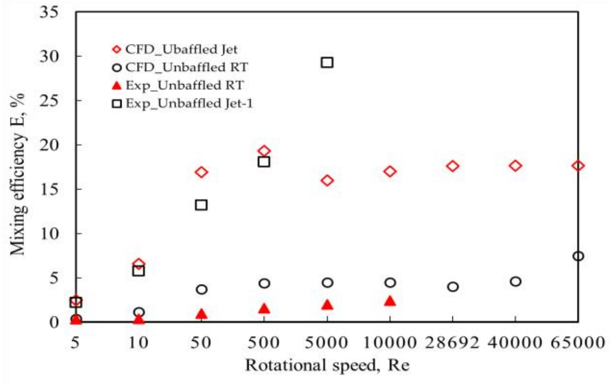

Fig. 6. Mixing efficiency *E* for Rushton turbine and Jet-1 impeller operating in a wide viscosity range.

The Reynolds number equal to 20 was indicated as the critical value for both turbines regardless of the distance from the tank bottom, for which the normalized pumping capacity has reached the highest value. The jet impeller (Jet-1) had significantly higher mixing efficiency than Rushton turbine, even at low rotational speeds.

All results obtained for the tested impellers (Figures 3-5) correspond to those obtained by other researchers. Analogical conclusions was presented Godlewska and Karcz [9]. They showed that for the Rushton turbine the power number presented as a function N_p=f(L/H) decreases with shorter length L of the baffles inside vessel.

3.2 Analysis of patterns flow using PIV

Figures 7-8 presents the pattern flows with local velocity vectors registered using with Particle Image Velocimetry in z-r cross-section plane and for tested impellers operating in high viscosity fluid (glycerine).
Based on the experimental results and PIV analysis for Ruston turbine, an intensive recirculation zone of fluid can be seen in the area of rotor motion, regardless of the position of the baffle or their absence. However, the flow pattern changes due to the presence of baffles inside the tank with a length that meets the condition L=H.
Figure 7 shows comparison of flow pattern for Rushton turbine operating in hight viscosity fluid for selected rotational speeds using tank with or without baffles.

Based on the previously study, it should be indicated that the power number increase with the length (L) of the baffles for fixed rotational speed and decreases with decreasing the position ratio s/H. The changes are clearly visible for the low Reynolds number analysed (Re<15), while for the effect of the presence of partitions, regardless of their length, is not significant for higher rotational speed [10].
The similar trend was observed for the standard case without baffles, where with increasing Reynolds number the power number N_p decreases significantly.
This is confirmed by the values of the calculated qualitative and quantitative parameters of fluid flow (N_p, K_c, E) - see Chapter 3.1
furthermore, clearly intensive radial and mixed flow can be observed as the rotational speed increases. The Rushton turbine is a radial flow impeller, but the use of four symmetrically placed baffles inside the tank resulted in a change the flow pattern to a radial-axial one. This mixed flow pattern is clearly visible in the PIV images (Figures 7 b,d).

The fluid flow ejected from the rotor zone is divided into two areas. The smaller belt is located below the impeller, where the fluid is subjected to strong recirculation. The second belt is located above the impeller (2/3 of the liquid column height), where the fluid, upon reaching the reinforced tank walls, is redirected upwards and then returns along the stator axis., is redirected upward and then returns along the stator axis. It should be noted that increasing the rotational speed increases the local flow velocities.

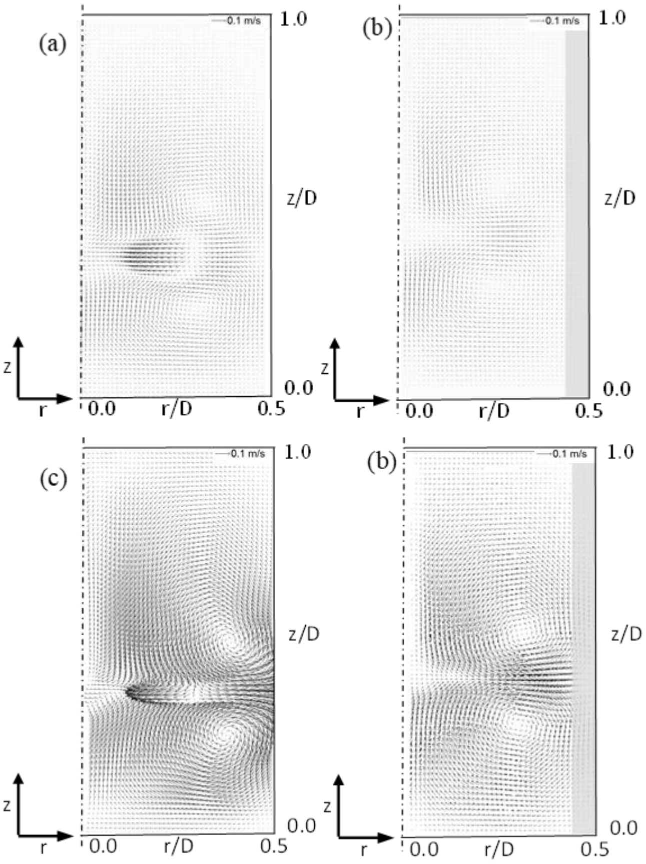

Fig. 7. Mean velocity field for Rushton turbine without baffled (a,c) and baffled of the tank (b,d) operating in glicerine for h/H=1/3 and rotational speeds N=100 rpm (top) and N=300 rpm (bottom).

The analysis of images PIV , it can be seen very strong and clearly (radial and axial) fluid motion in the whole domain cause by the Jet-1 impeller, while activity zone for Ruston turbine is much smaller. Additionally, the fluid flow for Jet-1 impeller is significantly enhanced in whole mixing tank , because there are no dead zones
As can be seen, different impellers generate very different flow movement.
Furthermore, increase rotational speed and positioning the impeller higher above tank bottom, can cause fluid to along the stator, creating a funnel (Figures 8d). This is unfavorable due to fluid aeration.

As you can be seen, different impellers generate very different flow motion.

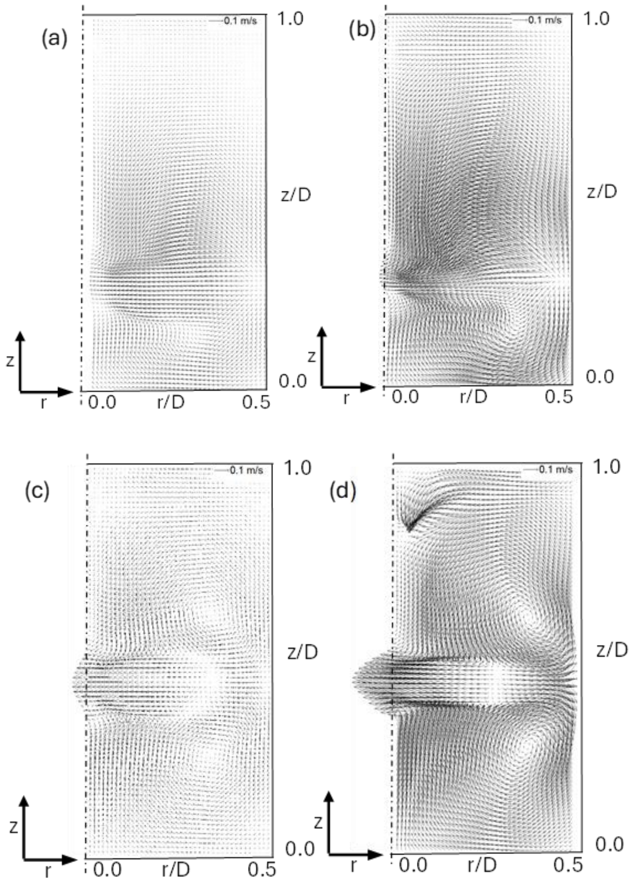

Fig. 8. Mean velocity field for novel impeller witout baffled of the tank and rotational speeds N=100 rpm (a,c), N=300 rpm (b,d) and h/H=1/3 (top), h/H=1/2 (bottom) oprating in glicerine.

4. Conclusion

In this research study, the main objective was to analyse the influence of tank geometry and impeller shape on the flow characteristics of a fluid with varying viscosity as well as the energy consumption and efficiency of the mixing process. Mixing efficiency was evaluated using flow velocity from Particle Image Velocimetry and Computational Fluid Dynamics simulations, while the required power was determined form torque measurements

Analysing the calculated values for the power number, normalised pumping power and mixing efficiency, it can be see that the presence of the baffles in the vessel have the important effect of mixing efficacy and energy demand. They confirmed it ,PIV measurements clearly showed that high viscosity liquid was mixed.

The obtained research results show that using modified impeller or tank designs can achieve high mixing efficiency with reduced energy consumption. These solutions can be universally applicable for mixing process with using the tank with or without baffles, especially for highly viscous liquids.

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Data availability statement. Data will be made available on request

Author contribution statement. A. Młynarczykowska : Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. M. Jaszczur : Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation, Supervision

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