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Impact of baffle geometry on the fluid motion in the stirred vessel

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Abstract. The fluids mixing is a crucial operation in a large number of engineering systems. It has major significance in chemical engineering, food, cosmetics and pharmaceutics production, biotechnology, wastewater treatment engineering, and countless other applications. Among many available systems online mixing with static mixers and stirred tanks plays a primary role and has been developed to meet several processing objectives. The effectiveness of the mixing process depends on a number of parameters, i.e. impeller shape, mixing phases properties, process conditions as well as stirred vessel design - in particular, number and baffles' design. The optimal baffles geometry is still an open issue and is usually design with trial and error methods. In this study, the focus is on the experimental investigations of the baffle geometry on the fluid flow and mixing phenomenon as well as on the required by the mixer power. In order to evaluate velocity field and mixing parameters, particle image velocimetry measurement is used whereas to obtain the power consumption by the stirred vessel precise torque meters were used. Measurements are carried out for different Reynolds numbers, to determine the most efficient process parameters. It has been shown that for the analyzed range of Reynolds numbers, the baffles design significantly influences fluid flow motion, mixing phenomena and the pumping number power number, but not affect the power number.

1 Introduction

Agitated tanks are widely used in chemical processes, food industry, pharmaceuticals, wastewater treatment, mineral and oil processing. The mechanical mixing is essential in selected processes as gas dispersion in liquids, the formation of suspensions and slow-sedimenting mixtures, prevention of sediment aggregation [1,2]. Depending on the type of mixed substances and the achievement of the assumed technological effect, different types of stirred vessel and impeller are used. Mixing, in general, fulfils two main objectives: technological and research. The technological aspect is the preparation of mixtures and the increasing efficiency of simultaneously occurring phenomena, chemical reactions, bioprocesses, dissolution, crystallization, cooling or heating. The research aspect is the creation of mathematical and physical models and optimization of the mixing process. The practical effect of the research is the development of new constructions of agitated vessels and rotors. Depending on the geometry and impeller speed, mixer produces a unique velocity profile: radial, axial or mixed. The most commonly used mixers are: turbine, propeller, foot, frame, etc. Their use depends primarily on the type of the mixing liquid and in particular on the liquid viscosity. Turbine and propeller impellers have the widest range of applicability. They can mix liquids or gas-liquids mixtures with an average viscosity range from 1 to about 10^4 mPa·s.

For this reason, the most-high-speed turbine agitators are commonly used in industry. Thus, they produce radial or radial-axial fluid flow. A special type is a disc agitator with blades - a Rushton turbine. Because of the high risk of the hopper formation and turbulence, in mixers quite often the baffles are used (usually two to four), which separate stirring areas. Researchers obtain a very good agreement between experimental and predicted mixing time over a wide range of impellers geometries or diameter and in the area of number blades, blade width and blade angle[3,4]. Thus, in addition to the stirred vessel geometry, the number, shape and position of the blades also have a significant impact on the power, efficiency and quality of mixing. It has been found that the optimal

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number of blades for turbine impeller is six. A larger number of blades in the turbine only slightly increasing the power mixing and has negligible impact on mixing phenomena.

Many researchers focus on the mechanical mixing. In the past, different solutions about the shape of the tank and rotor were tested only experimentally. Currently, thanks to advanced computational technology and based on mathematical models, the mixing process hydrodynamics can be predicted for more and more complex systems, replacing the time-consuming and expensive real experiments. However, due to the complexity of mixing processes, experimental verification of numerical modelling is still highly required as a final step of analysis or optimisation process [5].

In the literature large number, experimental and numerical investigation can be found. Scargiali et al. [6,7] studied the consumption of energy in the mixing process. Authors showed that the homogenisation process for mixture in a stirred vessel with rotation impeller without baffles does not require much electrical power. Jaszczur et al. [4] analysed the process of the fluid flow in the mechanically agitated vessel without baffles with new impeller type versus the Rushton turbine. The authors, as the basis for the assessment of the intensity degree and efficiency of mixing, used the analysis of velocity vectors distribution and power number. Based on an experimental and numerical study carried out for various stirred process parameters, it was demonstrated that the power number is at least 6-10 times higher for the Rushton turbine then for the novel impeller. This results in larger power consumption at the same rotational speed. On the other hand, the pumping number was calculated which depends significantly on the Reynolds number. Both these values show that efficiency defined as a ratio of pumping capacity Q_c to the power number N_p can be substantially higher for the tested novel impeller than for the Ruston turbine. In the literature, not much information can be found related to the universal applications of the stirred vessels with or without baffles, particularly for the very viscous fluids. In the case of very viscous fluids and when very important is high product quality not exist a lot of studies about using the vessel with baffles [8].

Godlewska and Karcz [9] for low viscous fluids showed that the value of the power number depends on the length L of baffles in the stirred vessel and that the Newton number is increasing as the length of the baffles increases. The influence of non-standard the baffles located inside the vessel was described in research studies Major i Karcz [15]

In the work of Nishikawa et al. [3], the correlation of mixing time with the number of baffles was examined by measuring the energy consumption by the rotor. This relationship was defined as a constant and characteristic for mechanical mixing. Based on the results, the authors concluded that if the width of the baffles is less than one-tenth of the length of the tank diameter, the optimal number of baffles are not less than three. The influence of the size of the baffle, the type of mixed fluid or the degree of aeration was studied by Lu et al. [10]. The presented numerical and experimental analyses showed that the uniform distribution of baffles and lack of air increases the quality of mixing. The authors also showed that there is not a universal number of baffles used that will be good for any mixing process.

Researchers agree, however, that the main task of baffles is to reduce angular velocity (fluid rotation in the vessel) and to cause additional turbulence which causes that the mixing process will be more intensively. The key, therefore, is to combine the high mixing enhancement with the mixer operating parameters, such as power consumption; type, amount and positions of baffles as well as fluid parameters like liquid viscosity [8]. Many studies describe laminar mixing, which can be a better solution in reference to high-speed turbulent more destructive mixing with typically required higher consumption of the power. In interesting studies, Ferrari and Rossi [11] measured the mixing efficiency in a quasi-turbulent flow via the experimental measurements of power input and output in the flow.

The mixing process can also be described utilizing numerical modelling by determining the distribution of mean and turbulent kinetic energy[13,1].

In literature, many research papers can be found in which researchers presented assessments of various turbulent models. It was found that the standard k–ε model under-predict the turbulent kinetic energy in the region of the rotor and failed to predict the mean flow associated with the strong vortex. The reason is that the models do not correctly describe the lack of fluid movement in the rotor area.

This paper presented selected results of the extensive analysis of different baffles configurations for variable rotor speeds and its optimal position. The goal was to obtain the best mixing process effectiveness. The presented analysis is based on the experimental measurements and include power number N_p, pumping capacity Q_r (two key parameters which describe mechanical mixing) as well as velocity fields for a selected cross-section from Particle Image Velocimetry (PIV) measurement.

2 Experimental set-up and methodology

Figure 1 presents the mechanically agitated vessel configuration. The dimensions of the chamber with the baffles used in experiments and also their location and the distance from the vessel bottom, are shown in Table 1. As a working fluid 100% glycerine (ρ=1261.1 kg/m^3, μ=1.4101Pa·s at 20ºC) as used.

Abbreviations used in Figure 1 are as follows: H-fluid level, D-inner diameter of stirred vessels, d-diameter of the agitator, h-distance between the agitator and bottom of the vessel, L-length of the baffle, s-distance between lower edge of the baffle and bottom of the vessel, w-width of the baffle, b-width of the agitator blade, a-height of the agitator blade. The thickness of the baffles and impeller was around 2 mm. The distance between the impeller and the bottom of the tank h was fixed and set at $^1/_3$H.

Table 1. Dimensions of the stirred vessels.

H mm	h mm	D mm	d mm	w mm	a mm	b mm	s mm	L mm
170	57	170	57	20	12	15	0-170	170-0

The agitated vessel investigated in this work has smooth cylindrical shape walls with the possibility of installing up to four baffles of various lengths and distances from the vessel bottom. As an impeller six-bladed Rushton turbine was used.

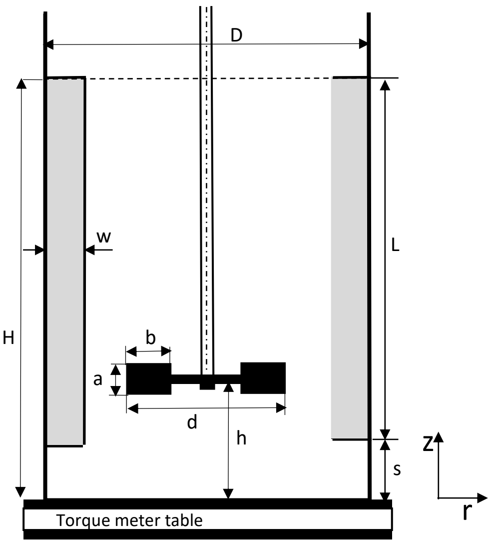


Fig. 1. Schematic diagram of the turbine and stirred tank.

In a first step the torque was measured by placing the impeller, by installed the stirred vessel on the measuring device with torque meter FSA-2 (AXIS, max 2Nm) enabling the measurement of the analysed impeller torque with the precision of 0.001Nm and sampling frequency of 1000 Hz. For verification of measurements on the rotor shaft was installed an additional calibrated torque transducer DATAFLEX 16 (KTR, max 10Nm, inaccuracies 0.001) connected to the data acquisition system National Instruments DAQ.

In the second step, velocity fields were measured using the Particle Image Velocimetry (PIV) method.

For evaluating, mixing efficiency the following parameters were determined from the experimental measurements Newton number (non-dimensional power number), flow field and pumping capacity Q_r. The instantaneous velocities in the vertical direction were measured in the cylindrical vessel, which was placed inside of the square tanks filled with water. PIV measurements were carried out for the constant position of the impeller and variable rotor revolutions and the presence or absence of baffles inside the vessel. All the measurement were performed for the fluid high H=D.

Because the fluid level increases with the agitator speed, therefore the only sub-critical range of impeller speeds was analysed to prevent air bubbles in the fluid.

The stirred vessel was illuminated with a double-pulse Nd:YAG laser of the energy of about 30 mJ per pulse. A vertical laser sheet of height 200 mm and the thickness about 1 mm was located through the centre of the tank. At current configuration, single CCD camera - La Vision with a resolution of 2048x2048 pixels was used. The PIV set-up after calibration procedures under fluid flow condition was testes in order to evaluate the minimum number of images required to ensure accurate mean velocity field. After analysis for laminar flow, the number of frames acquired with the CCD camera was set to 100 as a sufficient for low Reynolds number analysis (Re=10-160) presented in this paper. The methodology of PIV measurement described in detail in the paper Młynarczykowska et all. [12]

In the final step of experimental analysis based on the results two keys criteria numbers were evaluated: Power number N_p and Reynolds number Re. Those parameters designated according to the equations:

$$N_P = \frac{P}{\rho N^3 d^5} \quad ; \quad Re = \frac{N d^2 \rho}{\mu} \qquad (1)$$

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 (depends on the torque). Power was calculated from torque measurement as follows :

$$P = 2\pi \cdot N \cdot \tau \qquad (2)$$

where τ is the torque (N·m).
The last relevant parameter is the pumping capacity Q which dependents on the Reynolds number. It can be calculated for various Reynolds numbers through a cylindrical surface with a specified radius r or through the horizontal surface at specified heights z.
In this work due to impeller height variance more relevant is radial pumping capacity calculated through the cylindrical surface with a set point of radius r= 35 mm
Pumping capacity Q_r was evaluated through a vertical surface (radial pumping capacity and for the height z_1=0 and z_2=0,17 m using the relationship:

$$Q_r = \int_{z_1}^{z_2} |u_r| dS \qquad (3)$$

In the literature of the mixing, this parameter is also quite often normalise by the component $N \cdot d^3$. This quotient is the flow number, which represents the global flow characteristic.

3 Results and discussion

In order to correctly assess the efficiency and economy of fluid mixing the required power evaluation for the mixing process as a major parameter. Figure 2 shows the power number N_p evaluated for the Rushton turbine and for fixed impeller distances from the tank bottom equal to 1/3H i.e. about 57mm.

For this analysis, the impeller distance was fixed but the position of the four installed baffles above the bottom of vessel *s* was set at: ¼H (42mm),1/3H (57mm), ½H (85mm). Thus, the (active) length *L* of the baffles located inside of the cylindrical vessel (on the walls) was respectively, 3/4H, 2/3H, 1/2H.

Based on the results obtained, it can be indicated that the power number decreases with the position ratio s/H and increasing with the length (L) of the baffles for fixed rotor revolutions. However, the changes are very small and clearly visible only for the lowest Reynolds number analysed here. For the Reynolds numbers between 10 and 30 power number is almost independent on the length nor height of the baffle.

One can infer from this figure that the presence of baffles in the tank, regardless of their position during the measurement, did not cause significant changes in the evaluated power number for any of of the speed rotor analysed here. Similar results were observed for the case without baffles (L=0). Increasing Reynolds number, Power number N_p decreases significantly for all investigated cases including no baffle case.

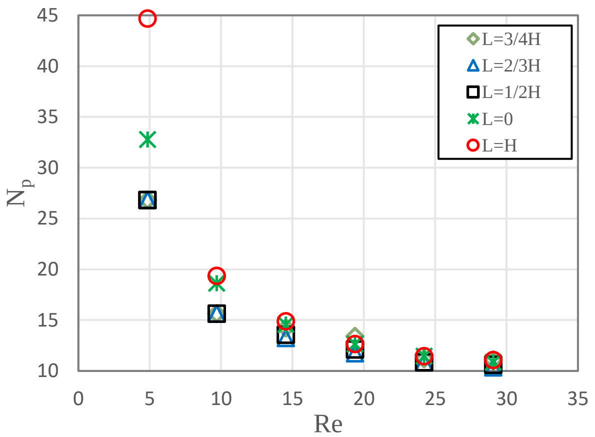


Fig. 2. Power number N_p for Rushton turbine and fixed impeller distances from the tank bottom h=1/3H and various baffles lengths or no baffles (L=0).

Figure 3 presents a radial of normalized pumping capacity Q_r/Nd^3. As can be seen, the pumping number values are small in the range from 0.099 to 0.20. The exception is the calculated and significantly different by remaining, Qr <1 value for Re> 14 for N = 300rpm

Analogy conclusion was presented Godlewska i Karcz [14] own research carried out for liquids of low viscosity. They tested the effects of geometrical parameters of the baffles in different positions from the flat bottom of the vessel. It showed that for the Rushton turbine function Np=f(L/H) decreases with shorter length L of the baffles. Worth noticing, that the power number of the standard Rushton turbine (the angle of blades is 90°) for an agitated vessel without of baffles it can be even twice as higher rather than for different angles of blades. However, overall they are numerically low values, especially for low viscosity liquids.

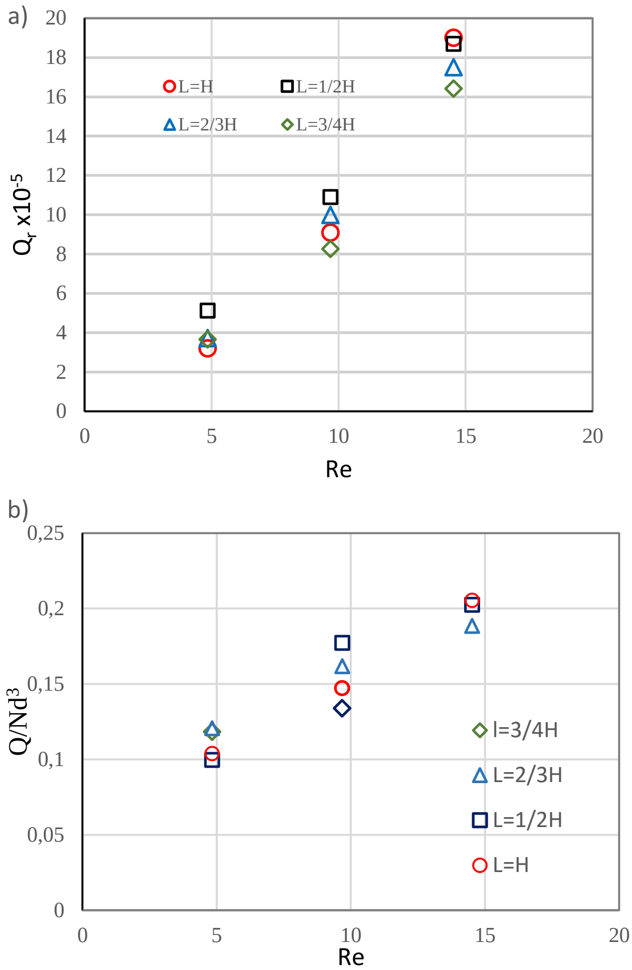
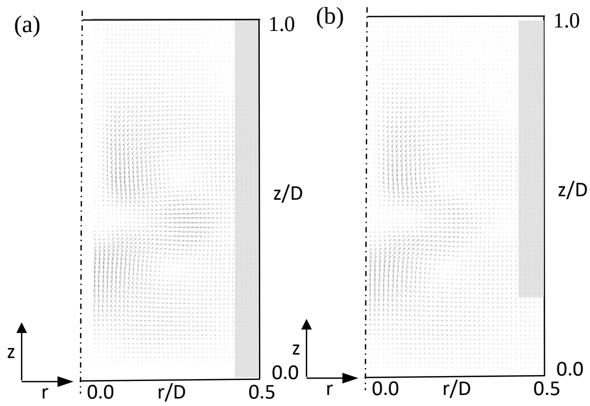


Fig. 3. (a) Radial pumping capacity Q_r for Rushton turbine in function of Reynolds number and for different position of baffles from tank bottom, (b) normalized pumping capacity $Q_r /N{\cdot}d^3$.

Figures 4-6 presentation of the velocity vectors evaluated with Particle Image Velocimetry in *z-r* cross-section plane and for tree rotational speeds *N*=100, 200, 300 rpm, for the 4 positions of baffles from bottom of the vessel s =0, s=¼H, s=⅓H, s=½H, the length of the baffle respectively is: L=H, L=3/4H, L=2/3H, L= 1/2H. The fluid intensive recirculation zone is seen in the area of rotor activity regardless of the position of the baffle. Clearly intensive radial and mixed flow can be observed as the rotor speed increases.



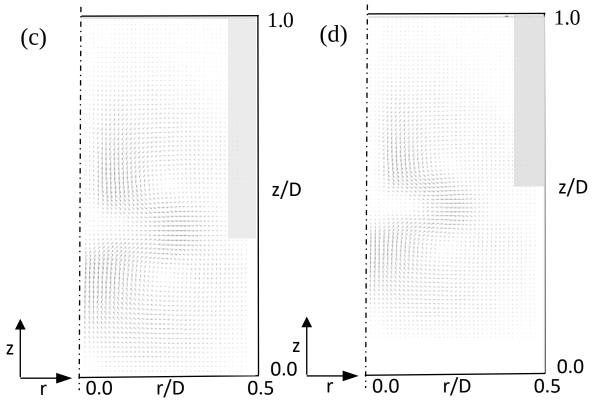


Fig. 4. Velocity field for *h/H*=1/3 Rushton turbine for rotational speed *N*=100 rpm and lenght of baffles: (a) L=H, (b) L=3/4H, (c) L=2/3H, (d) L=1/2H.

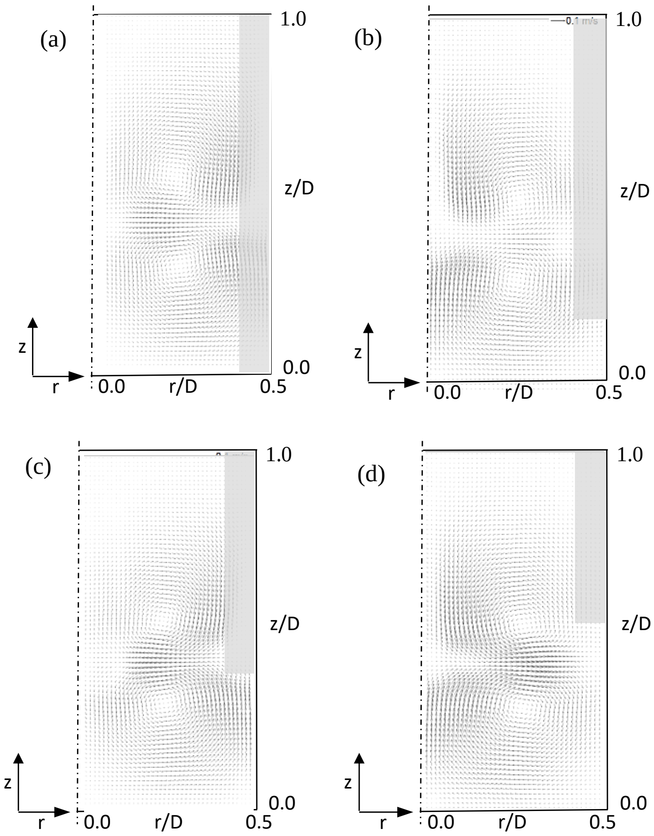
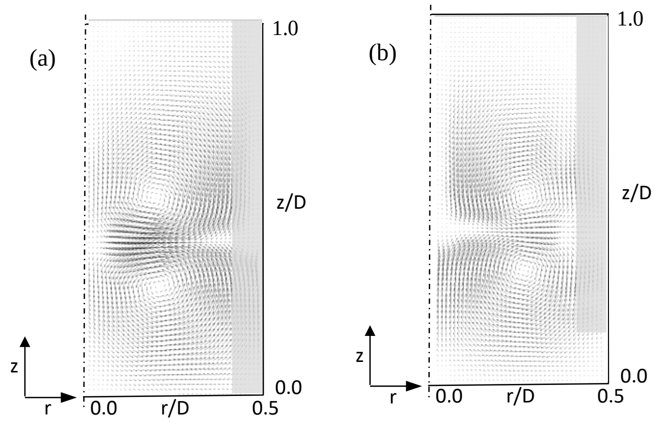


Fig. 5. Velocity field for *h/H*=1/3 Rushton turbine for rotational speed *N*=200 rpm and length of baffles : (a) L=H, (b) L=3/4H, c) L=2/3H, d) L=1/2H.



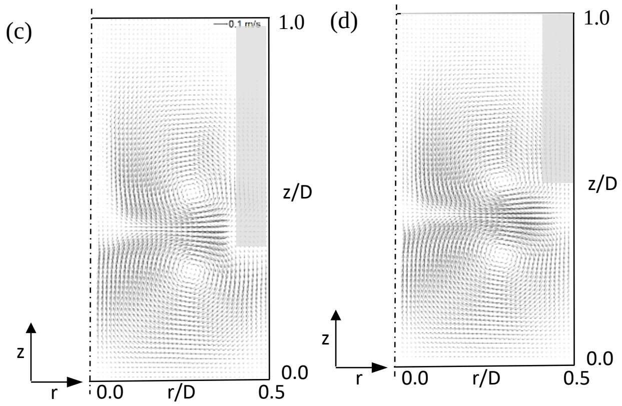


Fig. 6. Velocity field for *h/H*=1/3 Rushton turbine for rotational speed *N*=200 rpm and lenght of baffles (a) L=H, (b) L=3/4H, (c) L=2/3H, (d) L=1/2H.

4 Conclusions

This paper shows an experimental investigation of the mixing process for the high-viscosity liquid - glycerine. It was presented that the power number N_p depends on the Reynolds number (as the result of rotor speed) and only weakly on the length of the baffle inside the vessel.

The most substantial effect of tank geometry was found for the agitated vessel equipped with the baffles (L=H), where the power number decreases as an exponential function

Analysing the calculated values for pumping power and power number, it might seem that the presence of the baffles in the vessel (regardless of the location) does not have the important effect of mixing efficiency nor required power. However, PIV measurements clearly showed that the despite high viscosity of liquid, the fluid was mixed. Therefore, it is worth considering the use of a custom description for the fluid flow of different viscosity take into account the dynamic and mechanical parameters of the stirrer. The authors are going to investigate this issue in the subsequent studies.

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