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Ryszard Wójtowicz (rwojtowi@pk.edu.pl)
Institute of Thermal and Process Engineering, Faculty of Mechanical Engineering, Cracow University of Technology, Cracow, Poland

Andrey A. Lipin
Aleksandr G. Lipin
Faculty of Chemical Engineering and Cybernetics, Ivanovo State University of Chemistry and Technology

The performance of the Rushton turbine eccentrically positioned in a mixing vessel. Part I: the qualitative CFD analysis

Charakterystyka pracy mieszadła turbinowego Rushtona usytuowanego ekscentrycznie w mieszalniku. Część I: analiza jakościowa CFD

Abstract

A qualitative analysis of a liquid flow generated by a *Rushton* turbine eccentrically located in an unbaffled mixing vessel is presented in this paper. On the basis of *CFD* simulations the influence of the impeller position in the vessel on the flow pattern, velocity distributions and turbulence parameters are examined. Data are presented in visualisations and distribution maps created with various flow visualisation criterions. The results of this work can be used for the design and optimisation of mixing equipment applied in the industry.

Keywords: mixing, Rushton turbine, impeller eccentricity, flow circulation, CFD simulations

Streszczenie

Przeprowadzono jakościową analizę przepływu cieczy generowanego przez mieszadło turbinowe tarczowe Rushtona, usytułowane ekscentrycznie w mieszalniku bez przegród. Na podstawie symulacji numerycznych CFD określano wpływ położenia mieszadła w zbiorniku na wybrane parametry przepływu, tj. model przepływu, rozkłady prędkości cieczy czy też parametry burzliwości. Dane symulacyjne opracowano w postaci grafik wizualizacyjnych oraz wektorowych i konturowych map rozkładu, tworzonych w oparciu o różne kryteria wizualizacji przepływu. Uzyskane wyniki mogą być wykorzystane podczas konstruowania i optymalizacji aparatów z mieszadłami stosowanych w warunkach przemysłowych.

Słowa kluczowe: mieszanie, mieszadło turbinowe Rushtona, niecentryczność mieszadła, przepływ cieczy, symulacje CFD

1. Introduction

The *Rushton* turbine is one of the most popular impellers used in mechanically agitated vessels [1]. It is characterised by universality in use for various multiphase systems (gas-liquid, liquid-liquid or solid-liquid systems) and mixing effectiveness [2]. The primary issue for the description of the *Rushton* turbine's performance is the investigation and analysis of the quantities and parameters in a generated flow. They determine the efficiency of the mixing processes, e.g. breakup of drops, bubbles or suspension of solid particles. There are numerous papers focused on investigations/measurements of flow generated by the *Rushton* turbine in the literature [3–5]. In their experiments, the authors used different, usually advanced research techniques, e.g. *CFD* modelling [3], *Particle Image Velocimetry (PIV)* [4] or *Laser Doppler Anemometry (LDA)* [5]. However, most of these experiments were conducted in standard mixing vessels equipped with baffles of a standard design and geometry.

An interesting alternative to standard, baffled mixing vessels are unbaffled ones with eccentrically (not in accordance with the tank axis located) impeller [1]. The impeller displacement causes a change in the flow pattern in the vessel. Distinct, asymmetric circulation loops are induced in the apparatus. For identification of liquid flow generated by an eccentrically positioned *Rushton* turbine, numerical modelling and *CFD* simulations were applied. This study is a continuation of the research described in [6].

2. Computational model

The stirred vessel analysed in the numerical investigations is shown in Figure 1. It consists of an unbaffled cylindrical tank *1* (internal diameter $D = 0.286$ m) with a flat bottom. Inside the tank a single, standard *Rushton* turbine *2* was located (Fig. 1b). The impeller has the diameter $d = D/3$ and the impeller off-bottom clearance was set at $h = d$. The impeller rotated clockwise at $n = 300$ [1/min], in the range of fully turbulent flow ($Re_m \approx 4{,}5 \cdot 10^4$). Distilled water ($\rho = 998$ kg m^3, $\eta = 0{,}001$ Pa·s (at 20°C)) was taken as the tested liquid. The liquid height for all simulations was set at $H = D$. An impeller was located in three different positions inside the tank. Its distance from the tank axis was: $e = 0$ (central position, in accordance with the tank axis) as well as $e = 0.25R$ and $e = 0.5R$, where R is the tank radius. Flow identification in a stirred vessel was carried out based on results of numerical modelling, applying as a mesh generator *GAMBIT 2.4*. For all the mixing vessels tested an un-structural numerical mesh consisting of approximately $7.5 \cdot 10^5$ tetrahedral cells was generated. Model equations were solved using the numerical solver *FLUENT 6.3.26* and the finite volume *(FV)* method. The movement of the impeller was modelled with the multiple reference frames *(MRF)* mode. For a mathematical description of the turbulent liquid flow in a stirred vessel the standard *Navier – Stokes* equations were averaged using the *Reynolds* averaging *(RANS)* approach. Modelling of turbulence was carried out using – recommended for stirred vessels [7] – the *Realizable k-ε* turbulence model with standard wall functions. Detailed information on the mixing vessel design, methodology of simulations and their experimental verification is presented elsewhere [6, 7].

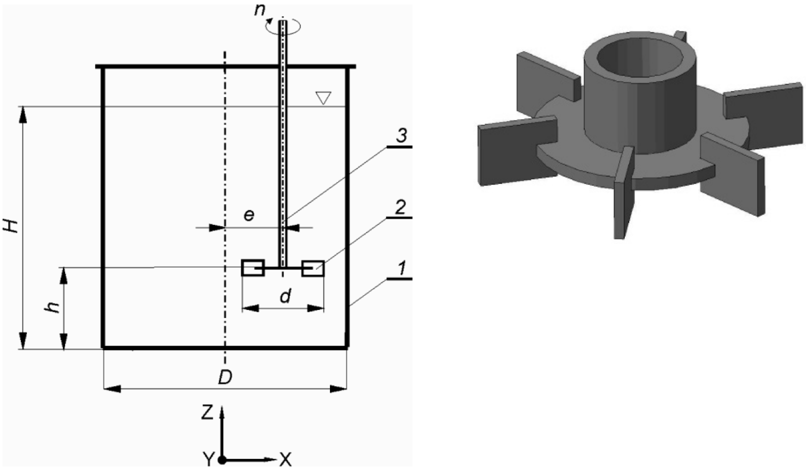

Fig. 1. Stirred vessel with an eccentrically positioned impeller: a) stirred vessel geometry: 1 – cylindrical tank, 2 – impeller, 3 – shaft, b) Rushton turbine

3. Results and discussion

The analysis of the flow generated by an eccentrically positioned *Rushton* turbine was conducted on the basis of qualitative visualisations, created with various flow visualisation criteria (iso-surface graphs, contour and vector maps).

For proper impeller design and structural calculations it is necessary to know the values of the pressure exerted by the liquid on the main elements of the impeller, such as blades, hub and disc. Figure 2 shows contour maps of the total pressure exerted on the *Rushton* turbine, located at positions investigated.

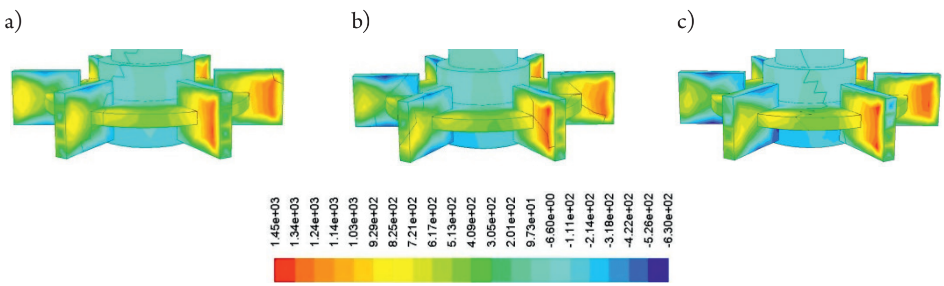

Fig. 2. Contour maps of a total pressure [Pa] exerted on eccentrically positioned Rushton turbine: a) $e = 0$, b) $e = 0.25\ R$, c) $e = 0.5\ R$

The maximum values of the total pressure – independently of impeller eccentricity e – are determined on the front sides of the blades, at the blade's tip. Slightly lower values are observed on the disc between neighbouring blades. On the rear sides of the blades, the pressure distribution is very differential. Close to the blade tip we can see narrow regions of positive values of pressure, while on the remaining area the total pressure is significantly lower and has negative values (underpressure). Underpressure maximum values were determined close to the top and bottom edge of the blade. The total pressure exerted on the hub and the shaft is low and negligible. Simulations did not show significant differences in the total pressure values with shaft displacement. When the impeller was positioned eccentrically (e = 0.25R or e = 0.5R) the maximum values of the total pressure on the front sides of blades were close (1443 [Pa] and 1448 [Pa] respectively), whereas when the impeller was in a central position (e = 0), the maximum values for the total pressure are slightly (about 5%) lower. Larger differences were observed in the values of underpressure (rear sides of blades). Maximum values of underpressure were determined for the largest shaft eccentricity (e = 0.5R) and differed in comparison with central shaft position (e = 0) by 30%.

During the *Rushton* turbine rotation vortices that differ in shape and scale are generated in the mixing vessel. Some of them have a scale comparable with the apparatus scale [6], the others are smaller and they are inducted in the impeller zone. A location of vortex cores can be visualised in a number of different ways, e.g. *Q*-criterion, λ – criterion or iso-surfaces of vorticity or helicity. Figure 3 presents example visualisations of trailing vortices generated behind *Rushton* turbine blades, created with the use of the *Q*-criterion. This criterion is defined as:

$$Q = \frac{1}{2}[|\Omega|^2 - |S|^2] > 0$$

where:

S – the rate-of-strain tensor and Ω is the vorticity tensor.

Each visualisation is prepared at the same scale (Q = 1500 [s^{-2}]). Iso-surfaces are additionally coloured by velocity magnitude.

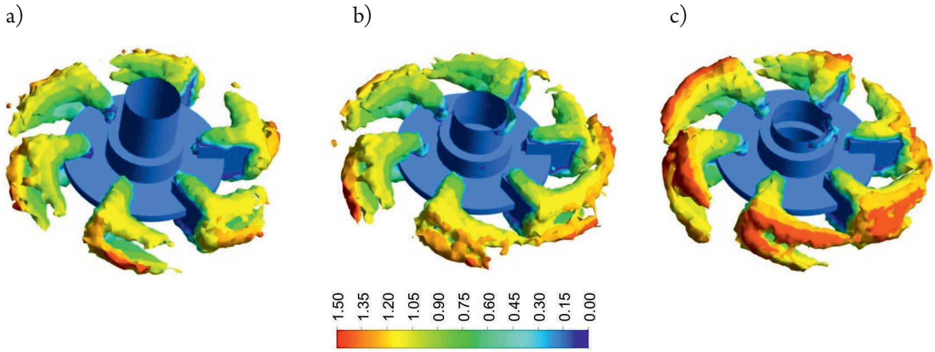

Fig. 3. Trailing vortices behind blades of an eccentrically positioned Rushton turbine (iso-surfaces of *Q*-criterion (Q = 1500 [s^{-2}] coloured by velocity magnitude [m/s], a) e = 0 , b) e = 0.25 R, c) e = 0.5 R

The movement of the impeller blades induces an intense flow in the blade zone. Firstly, liquid swirls are observed on the front side of the blades and close to the blade edges. Next, two separate, longitudinal trailing vortices above and below the impeller disc are generated. They are elongated in a tangential flow field. The biggest scale trailing vortices are seen for the highest impeller eccentricity e = 0.5R (Fig. 3c). For this case the greatest tangential velocities were also determined. The above-presented numerical visualisations of trailing vortices formation were confirmed experimentally, e.g. [1, 2, 8].

As a result of an impeller blade movement the main liquid flow is divided into a tangential flow and a radial one. Figure 4 presents velocity vector maps obtained for the vessel's vertical cutting plane (*XZ*), passing through the vessel axis and collinear with the impeller displacement. These maps show the distribution of velocity vectors for a radial-axial direction.

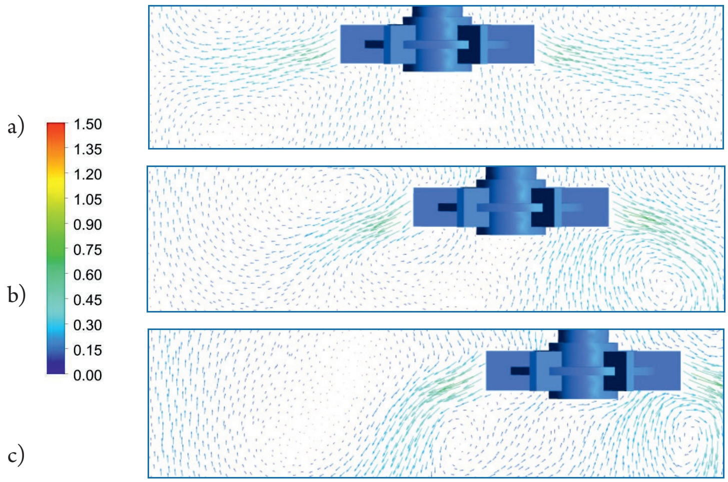

Fig. 4. Vector maps of flow inducted by eccentrically positioned Rushton turbine coloured by velocity magnitude [m/s], a) $e = 0$, b) $e = 0.25\ R$, c) $e = 0.5\ R$

With impeller displacement towards the vessel wall the flow pattern changes. For a central impeller position (Fig. 4a), the generated discharge streams are radial and symmetrical. Displacement of the impeller towards the vessel wall causes a visible deflection of the discharge stream to the bottom and a generation of small-scale vortices in the zone close to the tank wall, under the impeller (Fig. 4b, c). These changes and differences in the flow pattern were caused by the effect of the vessel wall and the generation of unsymmetrical, large-scale vortices, which are initiated in the impeller region [6]. Preliminary comparisons of these maximum values of tangential velocities (Fig. 3) with radial ones showed that tangential components are about 30% greater.

One of the parameters that characterise a turbulence flow in mixing vessels is turbulence kinetic energy *k (TKE)*. This quantity is often used for the estimation of impeller performance efficiency, characterisation of turbulence in an impeller discharge stream and also in dispersion processes. The contour maps presented in Figure 5 show changes of *k* with impeller eccentricity and confirm earlier described observations and tendencies. When the impeller eccentricity increases, the maximum values of *TKE* increase too (from 0.128 to 0.143 [m^2/s^2], 16%). For $e = 0.5R$ (Fig. 5c), the zones of high turbulence kinetic energy in the vicinity of the impeller are wider and they have greater scope. However, in this location regions of low *k* values are observed in the opposite part of the vessel. It is noteworthy that this paper mainly presents a qualitative analysis. In second part of this paper a full quantitative analysis of an eccentrically positioned

Rushton turbine performance will be presented, based on CFD modelling as well as Laser Doppler Anemometry (LDA) measurements. Also the advantages and disadvantages of the investigated solution in comparison with conventional, baffled mixing vessels will be discussed.

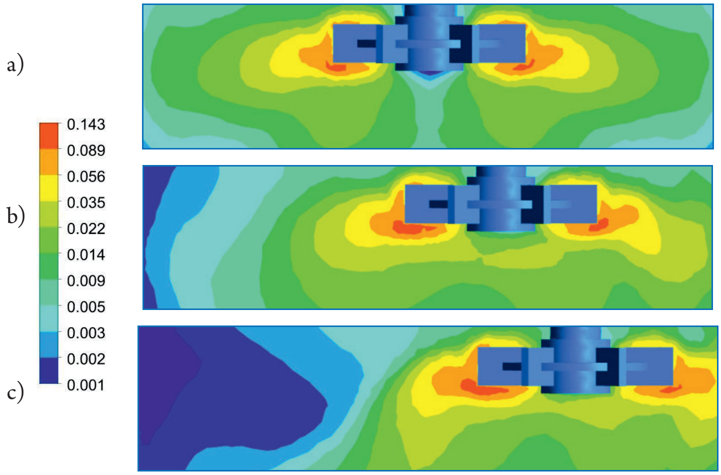

Fig. 5. Contour maps of turbulence kinetic energy k [m^2/s^2] for eccentrically positioned *Rushton* turbine: a) $e = 0$, b) $e = 0.25\ R$, c) $e = 0.5\ R$

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