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Analysis of the turbulent flow and trailing vortices induced by new design grooved blade impellers in a baffled tank

Sergio A. Martínez-Delgadillo[a,*], Alejandro Alonzo-Garcia[b], Víctor X. Mendoza-Escamilla[c], Israel González-Neria[d], J. Antonio Yáñez-Varela[d]

[a] Depto. Ciencias Básicas, Universidad Autónoma Metropolitana Azcapotzalco, Av. San Pablo 180, Azcapotzalco, CP 02200 México, D.F., Mexico
[b] CONACyT-Centro de Ingeniería y Desarrollo Industrial, Av. Playa pie de la cuesta 702, Desarrollo San Pablo, 76125 Querétaro, Querétaro, Mexico
[c] Depto. Electrónica, Universidad Autónoma Metropolitana Azcapotzalco, Av. San Pablo 180, Azcapotzalco, CP 02200 México, D.F., Mexico
[d] Posgrado en Ing. de Procesos, Universidad Autónoma Metropolitana Azcapotzalco, Av. San Pablo 180, Azcapotzalco, CP 02200 México, D.F., Mexico

HIGHLIGHTS

- The performance of two new design turbines with grooved blades 45° was evaluated.
- Dissipated power was reduced until 6% with new designs, compared with the 4PBT.
- The trailing vortices induced by new impellers were modeled with the DES approach.
- Validation of the modeling was carried out by PIV experimental tests.

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ABSTRACT

U or V shaped grooves have shown reduction in energy and power consumption in blunt bodies immersed in turbulent streams. In this work, the performance of two new design turbines with four blades rotated 45°, one with U and the other with V grooved shape blades, were evaluated in a baffled stirred tank reactor and they were compared with the one of the regular 4PBT. The power consumption, mean velocities, turbulent kinetic energy production (TKE), energy dissipation rate (ε) and trailing vortices induced by new design impellers with grooved walls and 4PBT were evaluated experimentally and modeled by detached eddy simulation (DES) approach, which has not been tested in blade walls with small perturbations. Validation of the results was carried out by PIV (Particle image velocimetry) experimental tests. The evolution of new and distinctive trailing vortices located in the upper and lower faces of the grooved new design impellers is presented. They were measured by angled resolved PIV technique, and visualized in three dimensions by the DES method. The V-grooves shaped impeller generated a larger region of influence of the turbulent kinetic energy along the discharge region than the other impellers. Moreover, presented higher mean dissipation rate levels for the most of the measured angles and induced higher number of trailing vortices in the blades vicinity than the other turbines. It was found that in a wide range of the Reynolds number (Re) ($40 \times 10^3 < Re < 125 \times 10^3$) the dissipated power measured experimentally from shaft, presented reductions of the order of 6% and 4% for the U and V grooved new models, respectively, compared with that of the regular 4PBT impeller.

1. Introduction

Agitated tank reactors (ATRs) are devices commonly used in chemical, mineral process engineering, food, and wastewater treatment industries with the aim of increasing the reaction rate and chemical-physical homogenization. While ATRs are easy to build and operate, the flow patterns induced by impellers are composed of a wide spectrum of temporal and spatial scales. For turbines with standard designs, a variety of work have been devoted to describe the mean flow and turbulent characteristics of the flow inside ATRs as function of variations in parameters as impeller diameter, clearance, eccentricity, number of baffles, blade angle and flow regime [1–4]. It is known that the impeller blades are responsible for the conversion of mechanical energy to momentum, defining hence the overall flow patterns and mixing characteristics present in the vessel. Thus, an analysis of its influence is a critical issue for designing purposes. In that sense, the mixing quality in an ATR relies greatly on the nature of the vortices created by the blades, its

* Corresponding author.
E-mail address: samd@correo.azc.uam.mx (S.A. Martínez-Delgadillo).

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position, the turbulence kinetic energy (k) and dissipation rate (ε) and its energy consumption. Works as those of Ge et al. [5] and Kumaresan and Joshi [6] have reported valuable calculations of parameters as power number (N_P), pumping number (N_Q), k and ε present in hydrofoil, Rushton or axial turbines with plane or slightly twisted blades. Nevertheless, in such works, the effect of small scale flow perturbations imposed on blades, which have been proven to be beneficial from an energetic point of view has not been addressed. Vasconselos et al. (1999) studied the turbulent flow induced under gasified or un-gassed conditions using a Rushton turbine with streamlined or perforated blades [7]. Depending among the design, the N_P is capable to decrease at expense of an increase in mixing time, at the same rotational speed. Also, diverse correlations between the inter-stage exchange number, N_P and mixing time were stablished. Ankamma Rao and Sivashanmugam (2010) reported power consumption reductions in a Rushton turbine when small triangular or rectangular slices are made in the blade tips, for a range Re from 50×10^3 to 200×10^3 [8]. According to the authors, such reductions are related to decreases in the shear forces that occur in the blade tips. More recently, Steiros et al. [9] and Başbuğ et al. [10], implemented direct numerical simulation (DNS) to analyze the effect of squared fractal shaped blades in a Rushton turbine. Authors obtained reductions in N_P, which in turn, were explained as function of changes in the recirculation wake formed behind the blades. So, it is recognized that with small scale wall modifications N_P can be reduced. Also, most of works have focused on wheel turbines. Another alternative not explored yet in order to reduce the drag forces and hence N_P in bodies influenced by an adverse gradient pressure is based on grooved surfaces. From an hydrodynamic point of view, grooved surfaces has proven to be capable of reducing shear forces and promote delay in the separation point on blunt bodies. For example, Lim and Lee [11], obtained a drag reduction of 19% in the subcritical flow over a circular cylinder, emulating the effect of the small scale riblets with sharp edges, which reduced drag in flat plates [12]. Thus, as the aerodynamic features of a circular cylinder (blunt body) found a large similitude with those of a rotating blade, and considering that the U and V grooves have been successful used as passive devices to obtain drag benefits [12,13], in this work, the performances of two new design axial impellers namely, U-grooved and V-grooved are evaluated. Both designs composed of four blades rotated 45° with grooves; one with U-shaped grooves and the other with V-shaped grooves. To gain insight about the velocity components, turbulent parameters and trailing vortices, produced by these new impellers, the angle resolved PIV technique was applied. In addition, N_P estimations based on torque measurements over the range ($40 \times 10^3 < Re < 125 \times 10^3$) were made. The results were compared with those of the regular 4PBT impeller. To understand the influence of grooved blades on the trailing vortices, the detached eddy simulation technique (DES) was applied. The main objective of this work is based upon the actual necessity of designing new type of turbines of simple manufacture capable of optimize mixing and decrease power consumption in long time operation mixing devices. Also, the angle resolved maps of velocities, turbulent variables, vorticity and trailing vortices could be used to validate the application of other turbulence models applied to walls with small scale perturbations.

2. Materials and methods

2.1. Impeller models

Two new different blade designs were tested and it performance was compared with a regular 4PBT impeller with plane blades. The new designs have groove blades, one with curved blades, resembling U-grooves, and the other with triangular V-grooves as shown in Fig. 1. For simplicity, during the rest of the document, the U and V grooved impellers will be named as U and V model respectively. The new design impellers dimensions are defined based on the blades width w = 14.3 mm.

2.2. Experimental arrangement and operational conditions

The experimental outline consisted of an acrylic SRT (T = 250 mm), four equally spaced baffles (B = 0.1 T) and an impellers (D = T/3, w = 14.3 mm and C = T/3). This is depicted in Fig. 2a. The working fluid used was water (ρ = 998.2 kg/m^3 and μ = 1.003 mPa·s). As a consequence of the refractive index effects the SRT was placed inside a cubic tank filled with the same level of water (H = T). The angular velocity was set to N = 500 rpm, at such conditions the flow was fully turbulent ($Re = \rho ND^2/\mu \approx 52{,}000$).

The velocity fields measured were acquired from a 2D PIV system (TSI Incorporated), integrated for a double-pulse Nd:YAG laser, that generates a beam with a wavelength of 532 nm and energy of 75 mJ per pulse. An optical array converts the round laser beam into a laser sheet of approximately 1 mm thick. 400 pairs of photos with a capture rate of 14 frames/s were taken with a high-resolution cross-correlation camera (2360 × 1776 pixels) with a time difference of 100 µs. The test section covered an area of ≈0.101 m × 0.075 m situated half way between two baffles, achieving a spatial resolution of ≈43 µm/px being the vector displacement of 0.69 mm. A shaft encoder was adapted to provide the trigger signal to the camera. In order to assess the angled resolved measurements, 18 planes located at different blade angles were measured (Δθ = 5°). The blade angle θ = 0° correspond to the mid-plane of a blade, Fig. 2b. TSI Insight 4G software was applied to analyze images via the Nyquist recursive grid algorithm, with an interrogation window of 32 by 32 pixels and 50% overlap between them. Torque measurements were acquired by a Futek FSH1980 rotary torque sensor with a maximum torque capacity of 1.41 N·m at a rate of 50 Hz, precision of 0.5%, with temperature control. The value used for calculations was the mean of 900 measurements.

2.3. Turbulent kinetic energy and dissipation rate calculations

In order to obtain turbulent data free from the periodic waves induced by blade motions, the triple decomposition procedure shown in the work of Sharp and Adrian [14] is applied by using Eq. (1). Here, u'' represents a fluctuating velocity component, U the instantaneous velocity being $\langle \widetilde{u} | \theta \rangle$ the average velocity obtained at a fixed blade position.

$$u'' = U - \langle \widetilde{u} | \theta \rangle \tag{1}$$

Because of the 2D PIV is not capable to measure the third velocity component and according with the pseudo-isotropic assumption of the turbulence, the k is calculated as function of the two measured fluctuating velocity components as shown in Eq. (2). Khan et al. (2006) verified negligible deviations between 2D and 3D PIV maps, for both, magnitudes and locations [15].

$$k = \frac{3}{4}(\overline{u''^2} + \overline{v''^2}) \tag{2}$$

The turbulence dissipation rate ε is composed of 12 terms, however from the 2 velocity components measured, just 4 terms could be obtained. In order to estimate the contribution of the non-measured velocity the turbulence is considered statistically isotropic. An interesting approach to calculate ε from 2D-PIV with spatial resolutions (Δ) larger than the Kolmogorov length scale $\lambda_K = (\nu^3/\overline{\varepsilon_T})^{1/4}$ is the large eddy approach [16]. In this method, the contribution of the scales smaller than the interrogation window of PIV is modeled by a sub-grid scale model which compensates ε values. In this work, the Eq. (3) as defined by Khan (2005) was implemented [17].

$$\varepsilon = (C_s\Delta)^2\left(4\overline{\left(\frac{\partial u''}{\partial x}\right)^2} + 4\overline{\left(\frac{\partial v''}{\partial y}\right)^2} + 2\overline{\left(\frac{\partial u''}{\partial y}\right)^2} + 2\overline{\left(\frac{\partial v''}{\partial x}\right)^2}\right)^{3/2} \tag{3}$$

The Smagorinsky constant C_s was adjusted for each impeller depending on the radio Δ/λ_k, according to Meyers and Sagaut [18]. From the experiments $C_s \approx 0.16$ for the three impeller models, so the 0.16 value was used as a constant. In the discussion of the results, the ε maps will be normalized with the tank averaged specific dissipation rate as $\varepsilon^* = \varepsilon/\varepsilon_T$. Here, ε_T (W/kg) was calculated for each impeller from the