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Numerical and experimental investigation of the self-inducing turbine aeration capacity

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ABSTRACT

Self-inducing turbines are a model of mixers that ensure the aeration of a fluid field without using a sparger and a surface aerator. Nevertheless, this type of turbines remain quite complicated in terms of behavior of the fluid within the tank, and its actual aeration capacity varies depending on the type of turbine used. The studied turbine is self-inducing and made of three blades and each blade contains five holes. In this work, we evaluated experimentally – using the technique of dynamic oxygenation and deoxygenating – the aeration capacity of our impeller by calculating the volumetric mass transfer coefficient k_La for various submergences and various inclination angles of the blade. This work was then validated by a numerical modeling using the commercial code Fluent, and the flow within the tank as well as the evolution of the hydrodynamic parameters was also studied. The simulation is steady state with a VOF multiphase model and the realizable k–ε turbulence model. We finally concluded that k_La decreases with the increase of the inclination angle and with the increase of the submergence of our turbine. We could also study the hydrodynamic parameters of the flow such as the power number, the aeration number and the shear rate.

1. Introduction

Many industrial processes rely on the mixing process and on the gas diffusion process, such as pharmaceutical industries, food manufacturers and waste-water treatment. The self-inducing turbine combines both the mixing and the gas diffusion in the same time. In fact, the hollow shaft of the self-inducing turbine allows gas to be introduced within the flow field, under the depression effect generated at the rear of the rotating turbine blades. The self-inducing turbines present the lowest cost in terms of maintenance, manufacturing and energy consumption. Many studies focused on the self-inducing turbines over the last years, and this both numerically and experimentally. In the early seventies, the concept of gas inducing agitators appears [1] and the studies begins to be more specific [2,3] to optimize this turbine performances. Researchers have begun to improve the design of these turbines [4–6] in order to improve the hydrodynamic parameters related to the flow generated by the self-inducing impeller. Later, studies have focused on the experimental and numerical study of various hydrodynamic parameters [7–10]. One of the most interesting hydrodynamic parameter is the volumetric mass transfer coefficient k_La, which tells us about the oxygenation capacity of a stirrer in a mixed tank. This coefficient was predicted either for the gas inducing reactors or for surface aeration. Studies focusing on this coefficient were lead first of all on stirred tanks with simple agitators and researches were essentially experimental [11–15], with various studied fluids [16–18] and various geometrical considerations [19–24] and different models of investigation [25,26]. And with the onset of self-inducing impeller, studies on the k_La have refocused around the evaluation of this parameter in an agitated tank by a self-inducing impeller. So hydrodynamics and mass transfer were studied on many works using various impeller designs [27–29] and various reactors [30] and different fluids [31–33], in order to propose a general correlation for the volumetric coefficient of mass transfer k_La [34–36].

This work reports a numerical and experimental investigation of the kinetics of gas–liquid mass transfer in a stirred tank equipped with an original design of self-inducing turbine, for different inclinations of the blades and for different turbine submersions. In this work we thought to enhance the profiles of the turbine blades which would normally allow a better acceleration of the fluid in contact with the blades, as they make it possible to ensure a lower friction

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coefficient. These new geometrical characteristics would normally provide better aeration capacity of our turbine. In this paper we want to confirm the high aeration capacity of our turbine, and this, for different inclinations blades and various turbine immersions. The air–water system at room conditions is chosen as model and the dynamics of oxygen mass transfer is studied both in absorption and desorption runs using nitrogen as stripping agent. The numerical study was elaborated using the commercial code Fluent, using the VOF multiphase model and the realizable k–ε turbulence model.

2. Experimental set-up

The widely used method to experimentally estimate the volumetric mass transfer coefficient k_La is the dynamic oxygenation and deoxygenating technique. This method consists in removing the oxygen initially present in water by introducing nitrogen using a diffuser located at the bottom of the tank, this will get the concentration of dissolved oxygen close to zero. Then the self-inducing impeller is rotating and the aspiration of air begins, and bubbles of oxygen appear in the stirred tank. The concentration of dissolved oxygen is monitored by a sensor and is recorded with a data acquisition system to subsequently determine the volumetric mass transfer of gas–liquid coefficient. The experiment stops when the saturation of domain is reached ($C_L = C_L^*$). The proposed technique uses kinetic measurements of dissolved oxygen evolution in the tank during stop phases of deoxygenation and oxygenation. Fig. 1 shows the curve of the kinetics of the ascent of dissolved oxygen concentration into the tank.

2.1. Experimental device

Fig. 2 shows the experimental setup used in this work. It is essentially composed of:

- A Plexiglas tank with a height $H = 45$ cm and a diameter $T = 36$ cm.
- A self-inducing impeller with 3 blade containing 5 holes (as shown in Fig. 3), with a height of $W = 3$ cm and a diameter of $D = 19.5$ cm. The hole diameter is $d = 0.4$ cm.
- A motor for rotating the moving agitator, with an adjustable speed of 50–2000 rpm.
- The deoxygenating is produced with N_2 through a diffuser at the bottom of the tank.
- An oxygen sensor to record the values of dissolved oxygen concentration.
- A switchboard can read dissolved oxygen concentration.

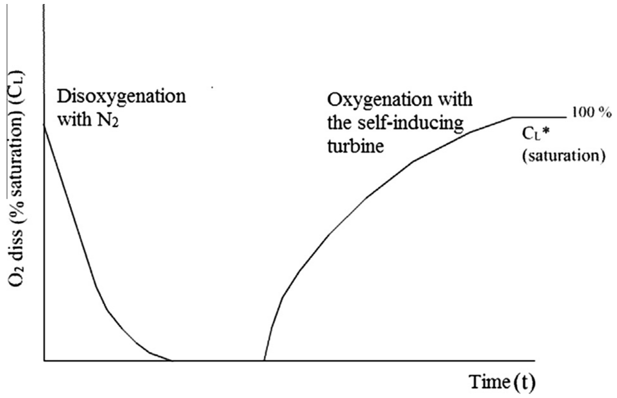

Fig. 1. Dissolved oxygen concentration ascent.

2.2. Methods of measuring the volumetric mass transfer coefficient

The value of k_La is determined via the dynamic method, using an oxygen meter probe, by measuring the concentration of dissolved oxygen change over time. Indeed, this method is based on the monitoring of the signal of an oxygen sensor over time, for example during oxygenation by continuous air aspiration through the moving agitator, or upon deoxygenating of a reactor saturated with oxygen by continuous injection of nitrogen. Determining k_La supposes the following assumptions:

- The liquid phase is perfectly mixed with the recirculation loops caused by rising bubbles.
- The response time of the sensor is negligible compared to $1/k_La$.
- C_L^* is constant.

The calculation of k_La can then be put into equations, so based on the above assumptions, we can write the mass balance of oxygen in the liquid phase:

$$\frac{dC_L(t)}{dt} = k_La(C_L^* - C_L) \tag{1}$$

The response time of the oxymetric probe is negligible, $C(t)$ is the concentration measured by the sensor, and the previous expression fits in:

$$\int_{C_{t0}}^{C_t} \frac{dC_L(t)}{C_L^* - C_L} = k_La \int_{t0}^{t} dt \tag{2}$$

and so we have:

$$-Ln\frac{C_L^* - C_L}{C_L^* - C_{L0}} = k_La \times t \tag{3}$$

Then:

$$\frac{C_L^* - C_L}{C_L^* - C_{L0}} = \exp(-k_La \times t) \tag{4}$$

As a result we have:

$$C_L^* - C_L = (C_L^* - C_{L0}) \times \exp(-k_La \times t) \tag{5}$$

and finally:

$$C_L = C_L^* - (C_L^* - C_{L0}) \times \exp(-k_La \times t) \tag{6}$$

From this equation we can determine k_La.

3. CFD model

To numerically study the flow field and the evolution of the volumetric coefficient of mass transfer k_La, a steady state and three dimensions simulations have been performed, using the VOF multiphase model and the realizable k–ε turbulence model.

3.1. Computational geometry

The studied field is a flat bottomed and baffled tank, equipped with a self-inducing turbine. The geometrical parameter and values have been already given in the previous section. The computational domain was carried out using the preprocessor Gambit. For the eight numerical cases studied, an extensive mesh-dependence study have been made, assuring us the independence between the adopted grid and the final obtained numerical results. Fig. 4 shows the final computational grid for an inclination angle $\alpha = 14°$ and a turbine submersion $s = 9$ cm. Fig. 5 shows the geometry of different blade inclinations angles α and Fig. 6 shows the final chosen mesh of the plane $y = 0$ for different submersions s.