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Gas-liquid mass transfer rates in unbaffled tanks stirred by PBT: scale-up effects and pumping direction.

Radim Petříček[a,*], *Libor Labík*[a], *Tomáš Moucha*[a], *Alberto Brucato*[b], *Francesca Scargiali*[b]

[a] *University of Chemistry and Technology, Prague, Chemical Engineering Dept., Technická 5, 166 28 Praha 6, Czech Republic*
[b] *Dipartimento dell'Innovazione Industriale e Digitale (DIID), Università degli Studi di Palermo – Viale delle Scienze, 90128 Palermo, Italy*

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ABSTRACT

Unbaffled stirred tanks are increasingly recognized as a viable alternative to common baffled tanks for a range of applications such as biochemical, food or pharmaceutical processes where the presence of baffles is undesirable for some reason.

In this work, the mass transfer performance of unbaffled stirred tanks with pitched blade turbine, operating either in up-pumping or down-pumping mode, was investigated. The influence of impeller size and liquid viscosity were also investigated.

The mass transfer intensity was measured by means of the Simplified Dynamic Pressure.
Method: The measurements concerned both coalescent and non-coalescent (viscous) batches.
Results: confirm that increasing apparatus size has a slightly positive effect on gas-liquid mass transfer coefficient. It was also found that when the PBT is operating in the up-pumping mode the formation of surface oscillations, which lead to undesired instabilities of the whole apparatus, is conveniently minimized. In the super-critical regime, the unbaffled tanks provide a performance comparable with that of the standard (baffled) bioreactors at the same power dissipation, which makes them a viable alternative for general fermentation operations and other gas–liquid reactions.

1. Introduction

Stirred tanks are widely used in the chemical and process industries. Crystallization operations, liquid–liquid extractions, leaching, biological fermentations and heterogeneous catalytic reactions are significant examples of industrial operations usually carried out in stirred tanks. In various applications, stirred tanks are required to fulfill several needs: blending of miscible liquids, dispersion of gases or immiscible liquids into a liquid phase, suspension of solid particles, heat and mass transfer promotion, chemical reactions, and so on. In order to satisfy different aims of the mixing operations, a wide range both of vessels and of agitators exists (Alcamo et al., 2005; Busciglio et al., 2010).

In the absence of baffles the liquid tends to mainly move along circular trajectories. As a result, only small relative velocities between impeller and fluid and weak radial flows are generated which, in turn, create a poor axial mixing. If a free surface is present, a pronounced vortex is formed on it, the depth of which depends on the rotational speed of the

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[*] Corresponding author.
E-mail addresses: petricek@vscht.cz (R. Petříček), francesca.scargiali@unipa.it (F. Scargiali).

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Nomenclature

Symbols

a	gas-liquid interfacial area per unit liquid volume, ($m^2\,m^{-3}$)
k_L	Mass transfer coefficient, ($m{\cdot}s^{-1}$)
k_La	volumetric mass transfer coefficient, (s^{-1})
C	Impeller clearance (m)
D	impeller diameter (m)
H	liquid height (m)
T	Tank diameter (m)
N	Impeller frequency, (s^{-1})
N_{crit}	critical impeller frequency for gas ingestion (s^{-1})
P	Power dissipation, (W)
Re	Reynolds number, (dimensionless)
V_L	Liquid volume, (m^3)

Greek letters

τ_P	Probe time constant, (s^{-1})

Abbreviations

DO	dissolved oxygen
SDPM	simplified dynamic pressure method
PBT	Pitched blade turbine
PVP	Polyvinyl pyrrolidone
RT	Rushton Turbine

stirrer and may become prohibitive at high speeds. The presence of radial baffles destroys the circular liquid patterns, thus inhibiting vortex formation; moreover, axial flows become much stronger and lead to an improved mixing rate. This is the main reason why baffled tanks are more widely used in industrial applications and have received far more attention both by experimentalists and by modelers.

Yet, there are cases in which the use of unbaffled tanks are desirable. First, baffles are usually omitted in the case of very viscous fluids ($Re< 20$), where they, giving rise to dead zones, would actually worsen the mixer performance, and where vortex formation is inhibited by the low rotational speed and by the high friction on the cylindrical wall (Nagata, 1975). Unbaffled tanks are also advisable in crystallizers, where the presence of baffles may promote the particle attrition (Mazzarotta, 1993; Busciglio et al., 2014). Finally, in bioreactor applications, when shear-sensitive cells are involved, mechanical agitation and especially sparging aeration (and associated bubble bursting) can cause cell death (Chisti, 2000; Nienow et al., 1996). In unbaffled vessels, at low agitation speeds, the required oxygen mass transfer may well take place through the free surface deep vortex produced by agitation (*sub-critical* conditions). This feature clearly makes unbaffled vessels potentially advantageous for shear-sensitive cultures (e.g., animal cell or filamentous mycelia cultures) as well as for foaming gas–liquid systems, provided that the process rates, and relevant gas consumption needs, are compatible with the relatively small gas transfer rates achievable. As a matter of fact, under such conditions, the oxygen mass transfer that takes place through the vortex surface was shown to be sufficient for typical animal cell cultures (Scargiali et al., 2014, 2015).

In ex situ soil remediation processes carried out in bioslurry reactors, sufficient oxygen transfer may well occur through the central vortex formation as an alternative to the adoption of gas spargers, which are intrinsically more troublesome (Tamburini et al., 2014, 2016). In fact, solid particles may form a muddy solid residue that blocks sparger holes or could cause wear of the sparger holes. Such phenomena favour the adoption of unbaffled reactors or gas inducing impellers (Conwayet al., 2002; Montante et al., 2013; Scargiali et al., 2012).

In a recent work, Labík et al. (2018) provided information on the influence on mass transfer performance of scale-up in unbaffled vessels stirred by a radial impeller (Rushton Turbine, RT). Results obtained with the RT were encouraging as, contrary to expectations, they showed that, for a given specific power input, similar (or even higher) mass transfer coefficients may be obtained in larger vessels.

Aim of this work is to verify whether the observed phenomenon also applies to impellers sporting an axial action. To this end in the present work scale-up effects on gas-liquid mass transfer in an unbaffled vessel stirred by a Pitched Blade Turbine (PBT, operated either in down- or in up-pumping mode) are presented and discussed. The impeller choice rationale lays on the fact that in a previous work, carried out on a small (lab-scale) vessel, the PBT turbine was found to be the best choice, among the stirrer types there investigated, for gas-liquid mass transfer promotion (Scargiali et al., 2014).

1.1. *Up- or down-pumping*

When dealing with axial impellers, the choice between up- and down-pumping is not always obvious, as there are various aspects that can affect the choice. Generally, in baffled tanks down-pumping axial impellers are considered to be more efficient than radial impellers for suspending solid particles, but this may not be the case in unbaffled vessels where the optimal choice between RT, PBT-up and PBT-down was found to depend on particle size and concentration, with PBT-up becoming more efficient at large particle concentrations.

When looking at gas-liquid mass-transfer performance, the optimal choice is even less obvious. Moreover, in a recent article free-surface oscillations in unbaffled vessels were observed and quantified (Busciglio et al., 2016). In industrial scale apparatuses such oscillations can lead to truly dangerous consequences, related to the periodical mechanical stresses of the whole apparatus. Thus containing such oscillations is highly desirable.

On the basis of the above considerations, one may wander whether: (i) mass transfer performance on scale-up is affected by the use of PBTs instead of Rushton Turbines in unbaffled tanks; (ii) the direction of pumping (up or down) affects mass transfer and how; (iii) the impeller choice may affect the insurgence of free surface instabilities.

2. Materials and methods

Two apparatus scales were used in this study, a laboratory scale with internal diameter $T = 0.19$ m (referred as T19) and a pilot plant scale apparatus with internal diameter $T = 0.48$ m (referred as T48). The investigated system was a transparent Perspex unbaffled tank filled liquid up to a height H equal to tank diameter D ($H = T$). A schematic diagram of the apparatuses employed is depicted in Fig. 1.

A four-flat-bladed (45°) turbine (Pitched Blade Turbine, PBT), with an impeller diameter D equal to one third of tank diameter T ($D = T/3$), was employed. A sketch of the PBTs employed