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Mass transfer and hydrodynamic characteristics of unbaffled stirred bio-reactors: Influence of impeller design

F. Scargiali*, A. Busciglio, F. Grisafi, A. Brucato

Dipartimento di Ingegneria Chimica, Gestionale, Informatica e Meccanica Università di Palermo, Viale delle Scienze, Ed.6, 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 processes where the presence of baffles is undesirable for some reason. For instance, in the case of shear sensitive cell cultivation (e.g. human cells), unbaffled tanks have been recently found to be able to provide sufficient mass transfer through the free surface vortex. As a consequence the need for bubble formation and subsequent bursting, along with relevant cells damage, is conveniently avoided. In this work the influence of impeller geometry on mass transfer performance and power demand of an unbaffled stirred vessel operating both in sub-critical conditions (the free surface vortex has not yet reached the impeller) and in super-critical conditions (the free surface vortex has reached the impeller and a gas phase is ingested and dispersed inside the reactor) is presented.

Experimental results show that the mass transfer performance of unbaffled systems is mainly affected by specific power consumption. Among the stirrer geometries investigated a simple PBT was found to provide the most interesting oxygen transfer performance in the sub-critical regime, and can therefore be regarded as a particularly suitable stirrer for shear sensitive cultures. As regards the super-critical regime, unbaffled tanks are found to provide a performance comparable with that of the standard (baffled) bioreactors, hence resulting in a viable alternative also for fermentations involving robust cells.

1. Introduction

Gas–liquid stirred vessels are widely employed to carry out aerobic fermentations as well as chemical reactions involving a gas reagent and a liquid phase. For low viscosity liquid phases the cylindrical vessel walls are typically equipped with swirl-breaking *baffles* (typically 4 baffles at 90° from each other) aimed at improving mixing performance. As a matter of fact in the absence of baffles (*unbaffled tanks*) a deep vortex forms on the liquid surface and relative velocities between the highly swirling liquid and the stirrer are quite low, so resulting into rather small pumped flow rates and in turn into poorer mixing than in baffled tanks.

Yet, there are cases in which the use of unbaffled tanks may be desirable, as for instance for crystallizers where the presence of baffles may promote particle attrition [1,2] and in precipitation processes where baffles could suffer incrustation problems [3]. They are also employed in food and pharmaceutical industries, where vessel cleanness is a topic of primary importance [4] and for the case of laminar mixing of viscous systems, typically in conjunction with large close-clearance impellers, since dead regions may form in the proximities of baffles [5]. Notably, when a suspended solid phase is present, higher values of the solid–liquid mass transfer coefficient may be obtained in unbaffled vessels, at the same value of mechanical power dissipation [6,7] and mechanical power required to achieve complete suspension is found to be smaller than in baffled vessels [8,9].

As concerns bioreactor applications, for aerobic fermentations and plant or animal cell cultivations liquid agitation is required in order to ensure oxygen and nutrient transfer and to maintain cells in suspension. When shear sensitive cells are involved, both mechanical agitation and sparging aeration can cause cell death [10]. Many studies on animal cell damage due to mechanical agitation and sparging aeration have shown that mechanical damage of freely suspended animal cells is, in most cases, associated with bursting bubbles at the air–liquid interface [10–12]. Gas bubbles are usually generated by direct air sparging to propagate oxygen in a culture suspension. Mechanical agitation may also introduce gas bubbles into the culture medium via vortexing entrainment from the liquid free surface. As an alternative, oxygen mass transfer may well occur through the free surface deep vortex which takes place when agitation is started. If this is not allowed to reach impeller blades (the free surface vortex has not yet reached the impeller, *sub-critical* regime, $N < N_{crit}$), bubble formation and subsequent bursting

* Corresponding author. Tel.: +39 09123863714.
E-mail addresses: francesca.scargiali@unipa.it, fscargiali@gmail.com (F. Scargiali).

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Nomenclature

a	gas–liquid interfacial area per unit volume of dispersion [m^{-1}]
k_L	oxygen mass transfer coefficient [$m\,s^{-1}$]
k_La	volumetric mass transfer coefficient [s^{-1}]
t	time [s]
t_0	initial time
t_p	oxygen probe time lag [s]
AGR	Advanced Gas Reactor
C_L^0	initial oxygen concentration in the liquid phase [$kmol\,m^{-3}$]
C_L	instantaneous oxygen concentration in the liquid phase [$kmol\,m^{-3}$]
C_L^*	equilibrium oxygen concentration [$kmol\,m^{-3}$]
D	impeller diameter [m]
DPM	dynamic pressure method
H	liquid height [m]
LDTSR	Long Draft Tube Self-ingesting Reactor
N	rotational speed [rpm]
N_{crit}	critical rotational speed [rpm]
N_p	power number [–]
P	power input [W]
P/V	specific power input [$W\,m^{-3}$];
PBT	pitched blade turbine
SDPM	simplified dynamic pressure method
T	tank diameter [m]
V	Tank volume [m^3]
Π	system pressure [Pa]
Π_0	initial system pressure [Pa]
θ_p	non dimensional oxygen probe time lag [–]
ρ_L	liquid density [$kg\,m^{-3}$]

inside the reactor is conveniently avoided [13]. The same feature clearly makes unbaffled vessels potentially advantageous for any foaming gas–liquid system, provided that process rates, and relevant gas consumption needs, are compatible with the relatively small gas transfer rates achievable. The same advantages pertain also to shake flasks and/or shaken microwell bioreactors [see for instance 11,14] where aerobic microbial fermentation is carried out in small volumes of nutrient broth and oxygen mass transfer occurs only through the free surface. These apparatuses are however suitable only for very small operation scales, incompatible with most industrial applications.

In three-phase mixing operations, the blockage of gas spargers by solid particles is a common issue, which can be avoided using an unbaffled reactor operating in aerated conditions, i.e. at rotational speeds larger than the N_{crit}, or a self-ingesting device [15,16]. As a matter of fact, solid particles can cause wear of the sparger holes, or the particles may form a muddy solid residue that blocks sparger holes. Such phenomena have adverse effects on the performance of the sparger and favour the adoption of unbaffled reactors or gas inducing impellers [17]. For similar reasons also many biotechnological processes can take advantage from the use of unbaffled reactors. In particular, when micro carrier spheres are employed to support cells, they can block the sparger holes. On the contrary, unbaffled stirred reactors operating in aerated conditions (the free surface vortex has reached the impeller and a gas phase is ingested and dispersed inside the reactor, *super-critical* regime, $N > N_{crit}$) may enable intensive liquid mixing and sufficient mass transfer coefficients without disadvantageous effects.

Notwithstanding the increasing industrial interest towards unbaffled tanks, available experimental information on unbaffled tank behaviour is still scant, even for basic quantities such as gas–liquid mass transfer performance, especially when no gas-sparging is present, as it occurs in the *sub-critical* regime. As a matter of fact, to the authors' knowledge only Cabaret et al. [18] measured the gas–liquid mass transfer performance in an unbaffled tank in which gas was continuously sparged. They investigated several dual impeller configurations, both co- and counter-rotating, either centred or off-centre. They found k_La values ranging from 0.01 to 0.06 s^{-1}, depending on configuration and gassing rate.

As regards un-sparged unbaffled tanks, the only available information is apparently that recently provided by the present authors [13], where preliminary results concerning data obtained with a Rushton turbine impeller are reported.

In the present work unbaffled vessels stirred by different impeller types are investigated. In particular the oxygen transfer rate and power consumption obtained under both *sub-critical* and in *super-critical* conditions, are reported and discussed.

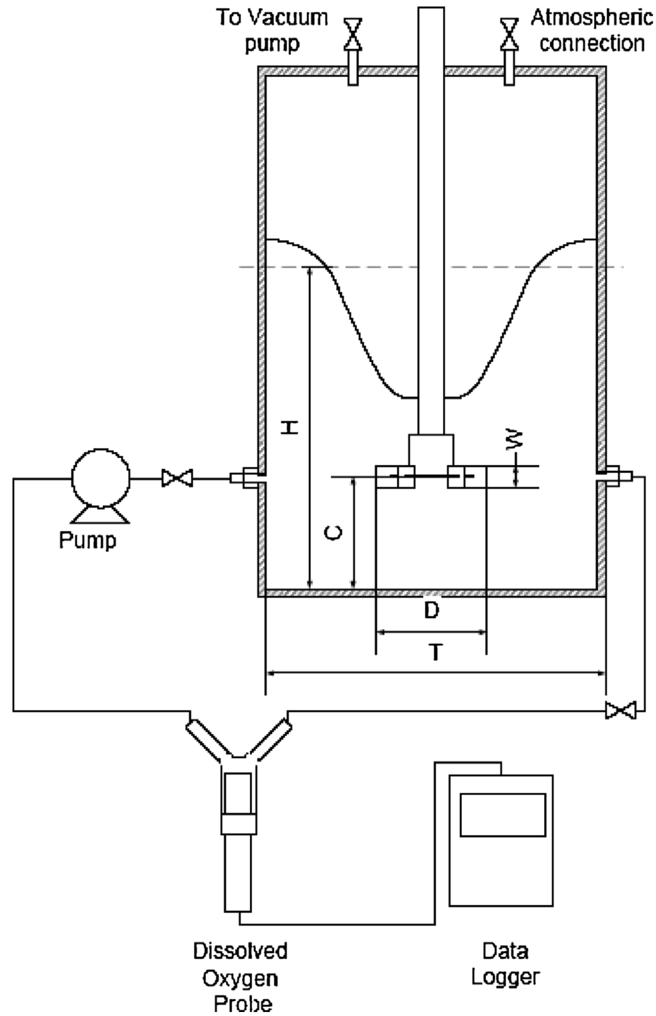

Fig. 1. Schematic diagram of the experimental apparatus.

2. Experimental

The experimental apparatus is depicted in Fig. 1. It involved a PMMA made cylindrical stirred tank (T = 190 mm) with a total height of 300 mm, provided with a stainless steel cover equipped with all inlet and outlet connections and a mechanical seal for shaft entrance. The vessel was filled with deionized water up to an eight of 190 mm (H = T) under no agitation conditions. Six different turbine types were mounted on the 17 mm dia. shaft, leaving a