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Power Requirements for Complete Suspension and Aeration in an Unbaffled Bioslurry Reactor

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Remediation of contaminated soils is spreading as a matter of crucial importance nowadays. Bioremediation via bioslurry reactors of sites polluted by recalcitrant pollutants has been proved to be a valuable option, although optimization is needed to reduce process costs. Free-surface unbaffled stirred tanks (with central air vortex) have been recently proposed as a promising alternative to the more common systems provided with baffles. In a bioslurry reactor solid-liquid interfacial area, oxygen supply, solid loading per reactor unit volume should be maximized, and, at the same time, operation costs have to be kept low. In this regard, the minimum impeller speeds for complete suspension N_{js} (suspension of all solid particles) and aeration N_{ca} (air vortex ingested by the turbine and dispersed as bubbles in the system) represents a reasonable compromise between process yield and power requirements. To this purpose, a flat bottomed unbaffled tank with diameter T=0.19 m was investigated. The tank was filled with water up to a height H=T. It was stirred by a radial six-bladed Rushton turbine~~s~~ (RT) with diameter D=T/3 and H=T/3. Mono-dispersed particles with diameter d_p=250-300μm and density $\rho \approx 2500$ kg/m^3 were employed. Solid loadings B% ranging from 2.5% (weight of solid/ weight of liquid) up to the very high 160% w/w were tested. The visual Zwietering criterion along with the aid of a digital camera was employed to evaluate N_{js} values. An acoustic criterion was adopted to assess N_{ca}. A static frictionless granite turntable was employed to measure the impeller torque at N_{js} and N_{ca} and to assess the relevant specific power requirements ε_{js} and ε_{ca}. Results show that the dependence of N_{js} and N_{ca} on B% is much lower at low solids loading (B<30%), while a larger dependence was found at larger B% values (B>30%). The relevant specific powers per unit mass of solids (i.e. $\varepsilon_{\cancel{js}}$ and ε_{ca}) were found to exhibit a minimum, at B≈20% for ε_{js} and B≈60% for ε_{ca}. On overall, data collected suggest that operating a radially stirred unbaffled bioslurry reactor loaded with a concentration B≈30% could be the best compromise to minimize the costs for achieving complete suspension and aeration conditions.

1. Introduction

A number of industrial sites have been dramatically polluted during the last century thus leading the interest towards novel and efficient remediation technologies to increase. The technologies making use of aerobic bacteria are commonly considered as particularly suited for soils contaminated by organic compounds such as hydrocarbons, pesticides, pharmaceuticals, etc. (Eweis et al., 1998; Rodríguez-Rodríguez et al., 2012). Unfortunately, the treatment times may be dramatically high when recalcitrant pollutants as polycyclic aromatic hydrocarbons (PAHs) are present. In this regard, bioslurry reactors are a bioremediation technology, which allows the concentration of this kind of pollutants to be reduced to very low values in reasonable times (Zappi et al., 1996; Lewis, 1993). Such systems are in fact provided with stirrers which, by agitating the slurry, increase transfer coefficients thus enhancing pollutants abatement rates (Cassidy et al., 2000). Bioslurry reactors have been seldom employed so far because of the high operation costs. In this regard, the optimization of the fluid dynamics in the tank may allow the costs to sensibly reduce and the technology to consequently spread. In bioslurry reactors for bioremediation, high solid-liquid ratios are employed and insufflation devices require frequent maintenance since the pores could significantly wear or even be clogged. For such kind of processes, free-surface unbaffled stirred tanks may represent a valuable alternative

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(Tamburini et al., 2012a). They are characterized by the presence of a central air vortex (*vortexing unbaffled tanks*). At low impeller speeds N, the vortex does not reach the stirrer (*sub-critical conditions*) and the oxygen supply occurs only through the vortex surface (Scargiali et al., 2013). The relevant volumetric mass transfer coefficient k_La was found to be much higher (more than one order of magnitude) than the case of a not agitated liquid system with free surface (Scargiali et al., 2014a) and this may be anyway sufficient for some processes (Scargiali et al., 2014b). As N increases, the vortex moves downwards in the central part of the tank. At a particular value of N named N_{ca}, air is ingested and dispersed throughout the tank, thus leading k_La to be largely enhanced. At $N \geq N_{ca}$ (*super-critical conditions*) the tank is at the same time agitated and aerated without the air sparger maintenance drawbacks typically occurring in the case of highly dense solid-liquid systems as bioslurry reactors. Moreover, suspension of the soil particles in the tank is a matter of crucial importance to improve the contact with the solid phase and consequently enhance the relevant mass transfer coefficients. In this regard, unbaffled systems have been proved to be less energy demanding than the traditional systems provided with baffles (Brucato et al., 2010; Wang et al., 2012).

On overall, in a bioslurry reactor solid-liquid interfacial area, oxygen supply, solid loading per reactor unit volume should be maximized, and, at the same time, operation costs have to be kept low. The aim of the present work is to find a good compromise which could represent an optimum among all these different aspects. The minimum impeller speed for complete suspension (suspension of all solid particles) N_{js} is well-known to be a good compromise between particle interfacial area maximization and agitation costs minimization (Davoody et al., 2015; Kasat and Pandit, 2005) also in biotechnological processes (Ibrahim and Nienow, 2004; Rafiq et al., 2013). Similarly, the minimum impeller speed for complete aeration (air ingested by the turbine and dispersed as bubbles in the system) N_{ca} represents a reasonable compromise between oxygen supply maximization and agitation costs reduction.

Therefore, in the present work N_{js} and N_{ca} were assessed along with their corresponding power requirements per unit mass of solids ε_{js} and ε_{ca}. By combining the above quantities, it would be possible to recognize the "optimal" soil loading guaranteeing at the same time lower power requirements for both complete suspension and aeration.

2. Experimental

A flat-bottomed unbaffled tank with diameter T=0.19m was investigated. The tank was filled of water up to a height H=T. It was radially stirred by a standard six-bladed Rushton turbine (RT) with diameter D=T/3 and clearance C=T/3. Mono-dispersed particles with diameter d_p=250-300μm and density $\rho \approx 2500$ kg/m^3 were employed. Bioslurry reactors are usually operated with high solid loadings in order to maximize the soil amount treated per unit volume of the reactor. Thus, solid concentrations B% ranging from 2.5% (weight of solid/ weight of liquid) up to the very high 160% w/w were tested in the present work. The tank was also uncovered and no gas-sparger was provided. As a matter of fact, a bioslurry system operating under aerobic conditions requires the oxygen consumed by the biomass to be suitably replaced (Leunen et al., 2002; Rodríguez-Rodríguez et al., 2012). In vortexing unbaffled tanks this may well occur through the central vortex gas-liquid inter-phase and through air bubbles surface, for systems operated at agitation speeds sufficient for air entrapping.

2.1 N_{js} assessment

The minimum turbine speed insuring the suspension of all particles (N_{js}) was assessed by the well-known "one second criterion" (Zwietering, 1958). A camera was placed underneath vessel bottom in order to collect a number of images (about 20) at each impeller speed. Camera exposure time was set to one second in accordance with Zwietering's criterion, so that motionless particles appeared to be well defined, while moving particle were blurred in the pictures. N_{js} was defined as the minimum impeller speed at which no well-defined particles were observable in all pictures (Tamburini et al., 2015).

2.2 N_{ca} assessment

N_{ca} is the minimum agitation speed at which the vortex reaches the impeller turbine plane and blades; this causes the air to be ingested and distributed throughout the whole vessel by the turbine rotation thus leading the system to become three-phasic (*complete aeration*). For the purpose of the present investigation a simple methodology was employed for the assessment of N_{ca}. It was named "*hearing criterion*" and is based on the noise produced by the rotating turbine while it is ingesting air. When the vortex depth reaches the turbine and the air is discharged by its blades, a clear hollow noise can be heard: the minimum speed at which this noise is heard is defined as N_{ca}. Some tests were repeated three times, also by different operators, and a surprising reproducibility was found: a maximum discrepancy of about 5% was found.

2.3 Power requirement assessment

Power measurements were performed by assessing the torque transmitted by the impeller to the tank with the apparatus described by Tamburini et al. (2014a). It is a “static-frictionless” turntable consisting of a granite dish able to rotate around its central axis on a granite table. This arrangement practically cancelled static friction between the surfaces, yet allowing dynamic friction to dump torque oscillations. Notably, power measurements were also performed in a corresponding tank provided with baffles for comparison purposes.

3. Results and Discussion

First results are shown in Figure 1 and concern the dependence of the minimal impeller speeds for complete suspension N_{js} (Figure 1a) and aeration N_{ca} (Figure 1b) on the solid loading. As it can be seen in Figure 1a, N_{js} values assessed in the vortexing unbaffled vessel are compared with those assessed in a corresponding baffled tank via the well-known Zwietering correlation. The values in the vortexing unbaffled tank are much lower than those pertaining the baffled tank. Values relevant to the baffled configuration are reported up to B=20%, since Zwietering’s correlation may be unreliable at large solid loadings (Tamburini et al., 2012b). Within this range (where comparison is possible), the dependence on of N_{js} on B% is higher in the baffled system (i.e. $N_{js} \propto B^{0.13}$) than in the unbaffled one (i.e. $N_{js} \propto B^{0.03}$). At larger solid loadings (B>20%, where only unbaffled data are reported), particle-particle interactions became prominent and rheology of the suspension allegedly changes thus leading to a much stronger dependence of N_{js} on B% (i.e. $N_{js} \propto B^{0.54}$).

Surprisingly, a similar behaviour was observed also for the case of the complete aeration speed (Figure 1b). More precisely, N_{ca} seems to be independent of solid concentration at low solid loading ($B \leq 30\%$), while for B>30%, solid concentration strongly affects the complete aeration speed N_{ca} (i.e. $N_{ca} \propto B^{0.95}$ for B>50%). This may be the consequence of a certain effect of solid particle concentration increase on vortex features, but additional data are needed to find an answer to this issue. In this regard, local data provided by CFD simulations might be a viable solution.

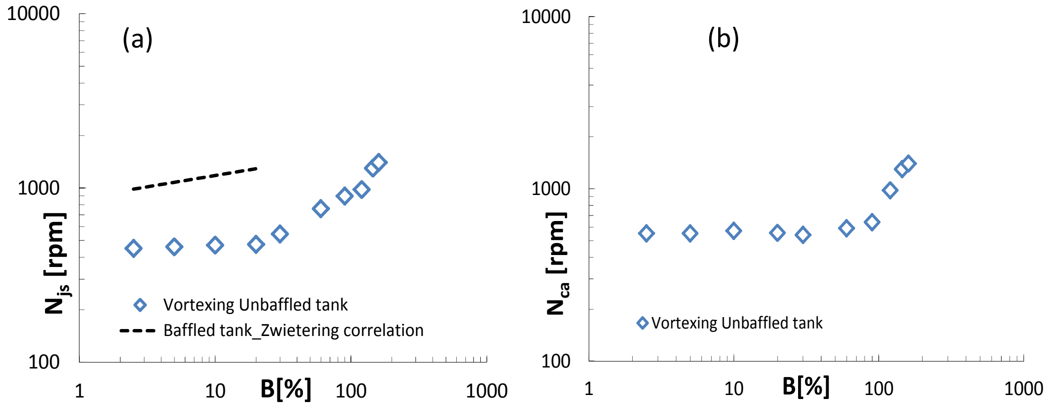

Figure 1: (a) dependence of N_{js} on B%; (b) dependence of N_{ca} on B%.

Complete suspension and aeration speed represent valuable information, although corresponding power requirements are more suitable to perform comparison among different geometrical configurations. Therefore, in Figure 2a, the minimum power requirements needed to suspend all particles (i.e. power measured at $N=N_{js}$) is reported as a function of solid loading. Also, the values experimentally assessed are compared with those relevant to a baffled tank stirred by a A310 stirrer which represents the most efficient configuration available for baffled tanks. The P_{js} values relevant to this specific baffled configuration are assessed by firstly calculating the N_{js} values by means of the Zwietering’s correlation whose geometrical value S is inferred from the data by Wong et al. (1987). Once the N_{js} values have been obtained, P_{js} values can be calculated from the power number expression ($N_p=P_{js}/(\rho_{susp}N_{js}^3D^5)$). For this A310-baffled configuration, N_p was estimated equal 0.36 from measurements performed at B=0%.

As shown in Figure 2a, the P_{js} values measured in the vortexing unbaffled configuration are much lower than those relevant to the best option available for baffled vessels, thus suggesting a significant economic convenience in adopting a configuration unprovided with baffles. On the other hand, a similar dependence of P_{js} on B% was found for the two configurations. Also in this case, the comparison only concerns values of B% lower than 20% since unreliable predictions may be provided by the Zwietering correlation at larger B% (Oldshue and Sharma, 1992).

The different power requirements between the baffled and unbaffled configuration is probably due to the different suspension mechanism which leads to different N_{js} values (the lower N, the lower P) but also to the different particle distribution in the two tanks. In baffled tanks solids are much better distributed throughout the tank (Tamburini et al., 2013a), although at N_{js} higher local concentrations may be located in the stirrer region. Conversely, in unbaffled tanks radially stirred, distribution is poor and particles are preferentially concentrated in some zones of the vessel which have been found far from the stirrer (Tamburini et al., 2013b) thanks to the higher centrifugal forces. Thus, the different distribution probably adds, to other geometrical and fluid-dynamic effects, another effect linked to the different apparent density seen by the impeller.

As concerns the P vs B% trend, as already observed in Figure 1a for N_{js}, P_{js} shows a lower dependence on B% at lower solid loadings (i.e. $P_{js} \propto B^{0.39}$ for B≤20%), while at larger particle concentration a slight increase in the value of B% results into a much larger power consumption increase (i.e. $P_{js} \propto B^{1.59}$ for B>20%).

A similar behaviour can be observed also in Figure 2b for the case of the power required for complete aeration conditions, P_{ca}: for B≤30%, P_{ca} exhibits a dependence on B% lower (i.e. $P_{ca} \propto B^{0.28}$ for B≤30%) than that pertaining the cases at B>30% (i.e. $P_{ca} \propto B^{1.65}$ for B≤20%). Notably, as a difference from N_{ca}, P_{ca} shows some dependence on B% also at low solid loadings: as the solid loading increases within the range 0-30%, the vortex reaches the impeller blades at very close agitation speeds, independently of the particle concentration, while the apparent density encountered by the impeller increases as B% increases. Thus, the increase of P_{ca} with B% within the range 0-30% is allegedly due only to apparent density effects rather than vortex features variations.

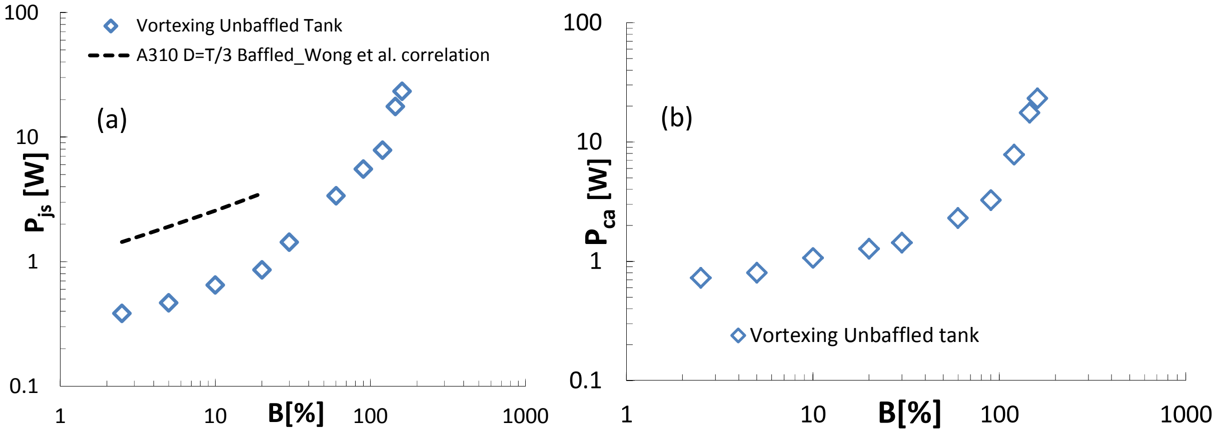

Figure 2: (a) dependence of P_{js} on B%; (b) dependence of P_{ca} on B%.

In bioslurry reactors it is important to minimize the remediation cost of an unit mass of contaminated soils. In this regard, power consumption per unit mass of solids is another important parameter that should be assessed. It can be easily estimated as the ratio between the power requirements and the solid loadings (Bong et al., 2015). With reference to our case, the specific power consumption for the just attained suspension of all particles (ε_{js}) and the specific power consumption for the just attained aeration of the tank (ε_{ca}) are parameters of great importance.

Their estimation allow to recognize which is the operating condition, in terms of solid loading, guaranteeing the largest cost savings. This can be easily inferred from Figure 3, which shows the dependence of ε_{js} (Figure 3a) and ε_{ca} (Figure 3b) on B%.

As reported in Figure 3a, ε_{js} exhibits a decreasing-increasing dependence on B%, thus resulting into a minimum at about B=20%. This value of B%, named B_{js}, should be regarded as the "*optimal solid loading condition for complete suspension*" at which the tank should be operated to minimize operation costs for complete suspension. It is worth noting that operating the tank at different conditions may result into dramatic increase of the specific power consumption. Just as an example, operating at B=2.5% results into more than tripling the specific power consumption and significantly reduce the process performance.

Analogous consideration can be done for the case of ε_{ca}: as shown in Figure 3b, also the ε_{ca} – B% trend is non-monotonic and exhibits a minimum which in this case occurs at B=60%. This value of B%, named B_{ca}, should be regarded as the "*optimal solid loading condition for complete aeration*" which should be adopted to minimize operation costs for the complete aeration of the system.

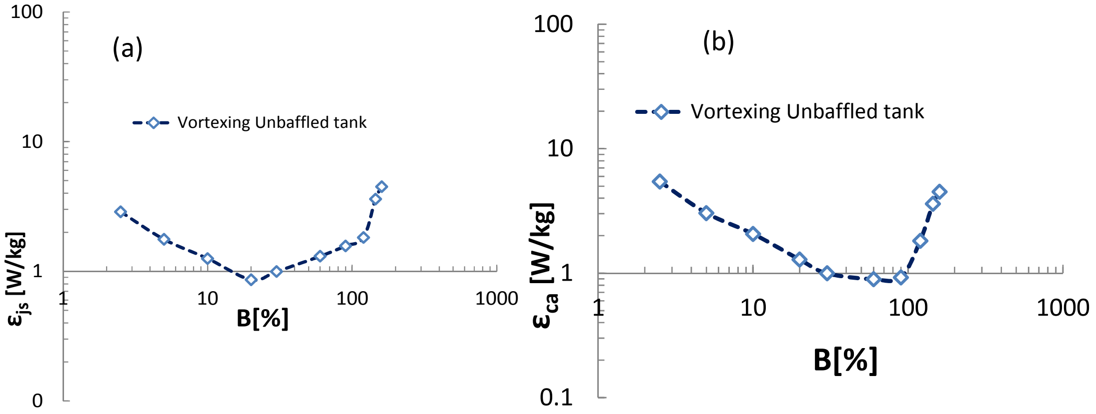

Figure 3: (a) dependence of ε_{js} on B%; (b) dependence of ε_{ca} on B%.

Since B_{js} and B_{ca} are different, the choice of the best operating condition cannot be performed without referring to the specific process under consideration. For instance, different processes (e.g. including different bacteria and substrates) may require different oxygen demand: when it is not high, the oxygen transfer via vortex surface might be sufficient and no complete aeration is required. Similarly, the burst of bubbles at the air–liquid interface may in some cases result into a damage for some cells (Chisti, 2000). Also, it is well known that operating some processes at impeller speeds slightly lower than N_{js} (Tamburini et al., 2011) may easily result into power savings which more than counterbalance the yield reduction due to the lower interfacial area (Tamburini et al., 2014b). In case both aeration and suspension are needed, operating the system at B=30% might represent a good compromise between the two aspects.

4. Conclusions

In the present work a free surface unbaffled tank stirred by a standard 6-bladed Rushton turbine was investigated. The possibility of adopting this apparatus as a bioslurry reactor was assessed by studying solid-liquid suspensions at different concentrations: in particular different solid loadings B% ranging from 2.5% w/w (weight of solid/ weight of liquid) to 160% were tested. The experimental work concerned the assessment of the minimum impeller speed for complete suspension N_{js} and the minimum impeller speed for complete aeration N_{ca}, conditions being both recommended for such systems. Moreover, power requirements corresponding to these two conditions were also measured in order to find the optimal concentration guaranteeing the lowest energetic costs for achieving both phenomena.

Results show that the dependence of N_{js} on solid concentration B% is somehow is low and similar to that found by Zwietering (1958) for the case of the baffled vessels up to B≈25%. Conversely, a much larger dependence was found at higher B%. As concerns the identification of the most convenient concentration value for complete suspension requirements, ε_{js} trends showed a minimum at B≈20%.The value of N_{ca} showed a negligible dependence on B% at low solids loading (B<30%), while a larger dependence was found at larger B% values (B>30%). The most convenient concentration for the complete aeration was found to be at B≈60%.

Therefore, details on the specific process under consideration are needed in order to recognize which is the controlling phenomenon between suspension and aeration and choose the relevant optimal concentration. When these details are not available or when both phenomena are equally important, it can be concluded that operating a bioslurry reactor loaded with a concentration B≈30% could be the best compromise to minimize the costs for achieving complete suspension and aeration conditions.

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