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Measurements of N_{js} and Power Requirements in Unbaffled Bioslurry Reactors

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The remediation of urban/industrial polluted lands is a topic of crucial importance nowadays. Bioremediation techniques are widely employed to remove organic pollutants from contaminated soils because of their simplicity and cheapness. The bioslurry reactors mechanically agitated by stirrers represent one of the most promising bioremediation techniques.

In the present work an unbaffled stirred vessel filled with solids and water is experimentally investigated from a fluid dynamic point of view. Air presence within the tank is guaranteed by the central vortex formation (typical occurrence concerning stirred vessels unprovided with baffles) instead of an intrinsically more expensive insufflation device.

Experiments were carried out aiming at assessing the minimum impeller speeds at which all solid particles get suspended (N_{js}) as well as the relevant power requirements (P_{js}).

N_{js} was assessed by adopting the well known “one second criterion” by Zwietering (1958).

Power measurements at complete suspension conditions (P_{js}) were carried out by assessing the torque transmitted by the impeller to the tank with the apparatus described in Grisafi et al. (1998).

The dependence of both parameters on system geometrical configurations (impeller diameter, impeller clearance and impeller type) were investigated.

Results were compared with relevant literature ones obtained for the case of the more common baffled systems suggesting that from a fluid dynamic point of view, biodegradation operations can be conveniently conducted in unbaffled stirred vessels.

Finally, the P_{js} values collected show that a tank stirred by a six-bladed Rushton turbine with a diameter equal to one third of tank diameter and a clearance equal to one third of tank diameter is the most economical configuration among the ones investigated in the present paper.

1. Introduction

Soil remediation technologies importance has kept increasing in recent years due to the increasing awareness of problems associated with industrial polluted soils. The interest towards the remediation techniques has allowed the development of different removal methods based on chemical, physical, thermal and biological treatments, or their combination.

Traditional *in situ* procedures are not always feasible as the low permeability and heterogeneous nature of the soil permit such procedures only in a limited number of cases.

On the contrary, *ex-situ* remediation technologies based on *bioslurry reactors* (biological reactors operating in slurry phase) have been found to be encouraging for the treatment of soils contaminated by many pollutants, such as pesticides, diesel fuel, petroleum hydrocarbon, solvents, lubricating oils, polycyclic aromatic hydrocarbons, etc. (Eweis et al., 1998). The contaminated soil is mixed with water,

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nutrients and oxygen (or simply air) and other additives in a bioreactor. Bio-slurry reactors are commonly equipped with process control systems devoted to create ideal conditions for the biodegradation, thus guaranteeing very high degradation rates also for recalcitrant pollutants.

Bioslurry systems are often operated on the basis of an empirical approach. Optimal operating conditions are searched by extensive trial and error procedures, involving costs so large that their widespread use is inhibited.

Therefore, research main goal is to find "optimized" conditions for the operation of such systems. Among the others, fluid dynamic aspects have a crucial role in determining the performance of a bioslurry system. For instance it is essential to guarantee the suspension of all solid particles (in order to ease mass transfer processes) as well as to minimize the mechanical power dissipation. The optimization of these aspects is represented by the minimization of the power required to suspend all the solids P_{js} (Brucato et al., 2010).

The present work is actually devoted to finding the optimal geometrical configuration (impeller type, diameter and clearance) able to provide the lowest value of P_{js} for the case of a mono-dispersed soil in an unbaffled stirred tank.

2. Experimental

The investigated system was a transparent Perspex unbaffled tank with a diameter T = 0.19 m agitated by radial six-bladed Rushton turbines (D = T/3 or T/2) or by axial A310 impellers (D=T/3 or 0.45T), offset from vessel bottom by either T/3 or T/10. 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. 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 (Scargiali et al., 2012). The vessel was filled with weighed quantities (2.5, 5, 10 and 20 %, solids-weight/liquid-weight) of silica particles (250–300 μm) and deionized water was added up to an height H=T at no-agitation conditions. As a difference from Brucato et al. (2010), Tamburini et al. (2009) and Tamburini et al. (2011), who employed a freesurface-less closed vessel, in the present work the unbaffled vessel employed was uncovered. As a consequence, a more or less pronounced (depending on agitation speed) central free-surface vortex was observed.

2.1 N_{js} assessment

The minimum impeller 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 images 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. The use of the camera and of the relevant acquired pictures for the N_{js} assessment largely reduces the subjectivity of Zwietering's criterion, as already stated by Brucato et al. (2010) who proposed the *Steady Cone Radius Method (SCRM)* for N_{js} assessment in top-covered unbaffled vessels. In the present system a central cone of unsuspended particles was observed only when the T/2 Rushton turbine was employed. As a consequence the SCRM (Brucato et al., 2010; Tamburini et al., 2011) was here adopted only for this case.

2.2 Power measurement

Power measurements were performed by assessing the torque transmitted by the impeller to the tank with the apparatus described by Grisafi et al. (1998). 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.

3. Results and Discussion

The dependence of N_{js} on solids concentration B% for D = T/3 Rushton Turbine offset by 1/3 and 1/10T from vessel bottom is shown in Figures 1 A and B respectively (empty circles). As it can be seen, N_{js}

slightly increases when increasing average solids concentration, as expected. For comparison purposes, on the same figures the N_{js} values pertaining to the *baffled* tank, as obtained by several variants of the well known Zwietering's correlation (Zwietering, 1958; Ibrahim and Nienow, 1996; Armenante et al.,1998) are shown.

As it can be seen in Figure 1A the collected N_{js} values are significantly lower than those relevant to the baffled tank. This is clearly related to the striking difference between the flow fields obtained in presence or absence of baffles. The dependence of N_{js} on B% in the unbaffled tank appears to be slightly lower than that pertaining baffled tanks, a feature that might allow easier operation at high solids concentrations.

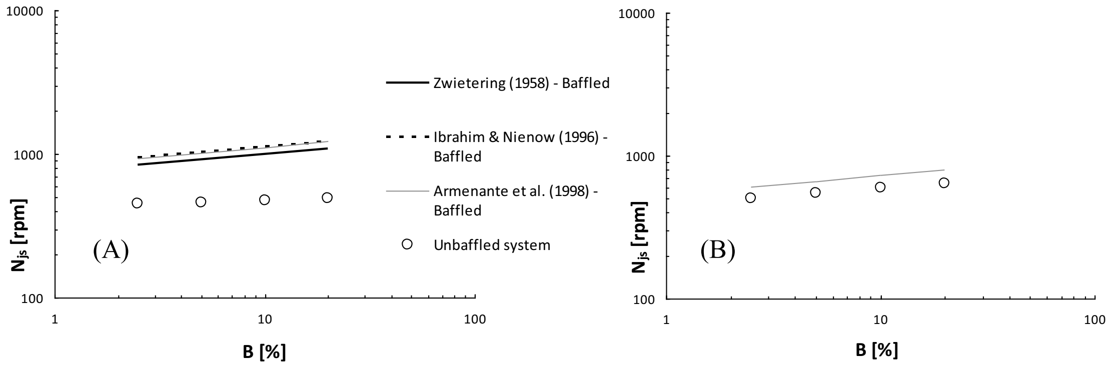

Figure 1: N_{js} vs B for the case of the Rushton turbine (D=T/3): (A) C=T/3; (B) C=T/10

As regards the data obtained with the lower impeller clearance (C = T/10, Figure 1B) the gap between baffled and unbaffled N_{js} values is greatly reduced: unbaffled N_{js} values are found to be slightly lower than those predicted by Armenante et al. (1998) correlation (who were the only ones that explored also the C = T/10 case). It is worth noting that for baffled vessels N_{js} is much lower at C = T/10 with respect to C = T/3 (Armenante et al. 1998), a feature possibly due to the flow pattern transition from double to single loop. As a difference, in unbaffled vessels much closer N_{js} values at the two investigated impeller clearances are found. Finally, the dependence of unbaffled N_{js} on B% at the shorter clearance (Figure1B) seems to be closer than at C = T/3 (Figure 1A) to that observed in baffled tanks (N_{js} proportional to $B\%^{0.13}$).

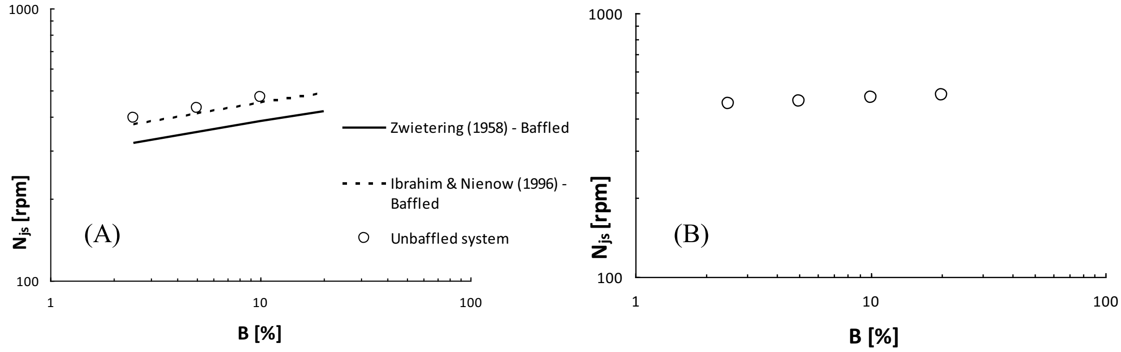

Figure 2: N_{js} vs B for the case of the Rushton turbine (D = T/2) : (A) C = T/3; (B) C = T/10

Results obtained with the D = T/2 Rushton turbine are shown in Figures 2A and B, for C = T/3 and C = T/10 respectively. In Figure 2A it can be seen that, for this larger impeller, unbaffled N_{js} values are no longer smaller than the relevant baffled vessel values, a difference with the previous case that might be related to a difference in the flow patterns generated by the smaller and larger impeller in the vicinities of tank bottom. As already observed in Figure 1, the collected N_{js} values appear to be only slightly dependent on impeller clearance. Finally, the dependence of N_{js} on B% is found to be similar for the two systems.

In Figures 3 and 4 results obtained with the A310 impeller are shown. As it can be observed in Figure 3, very similar N_{js} values were found for the two systems (Figure 3A), while the N_{js} values collected in the unbaffled tank are somewhat larger than those for the baffled tank when C = T/10 (Figure 3B). As already observed in Figure 1, the adoption of a low impeller clearance causes a reduction of the N_{js} values only for the case of the tank provided with baffles, while no appreciable variations are observed in the unbaffled vessel.

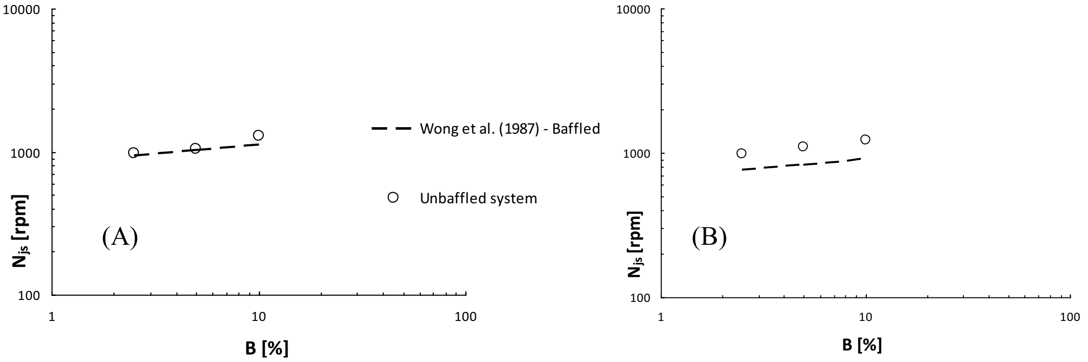

Figure 3: N_{js} vs B for the case of the A310 impeller (D = T/3): (A) C = T/3; (B) C = T/10

As far as the 0.45T A310 impeller is concerned, Figure 4A shows that the N_{js} measured in the unbaffled bioslurry system are lower than those predicted for the corresponding baffled system. Also in this case, N_{js} was found to be only slightly dependent on impeller clearance (Figure 4B).

Notably, a similar dependence of N_{js} on B% for the two systems was found for all the data obtained with A310 impellers (Figures 3 and 4).

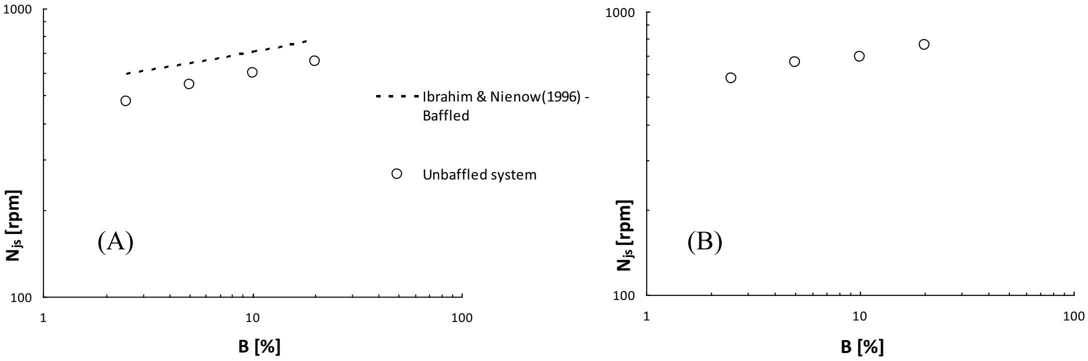

Figure 4: N_{js} vs B for the case of the A310 impeller (D = 0.45T): (A) C = T/3; (B) C = T/10

Summarizing, the N_{js} values which can be obtained in unbaffled vessels are similar or lower than those relevant to corresponding baffled systems for the case of an impeller clearance equal to T/3.

For the case of baffled tanks, the lower the impeller clearance, the lower the impeller speed, while in unbaffled tanks, N_{js} was found to be scarcely affected by impeller clearance.

Moreover, the average dependence of N_{js} on particle concentration B in the unbaffled systems ($N_{js} \propto B^{0.12}$) is very similar to that commonly obtained with baffled systems ($N_{js} \propto B^{0.13}$) and this might be related to a similarity in the underlying suspension mechanisms.

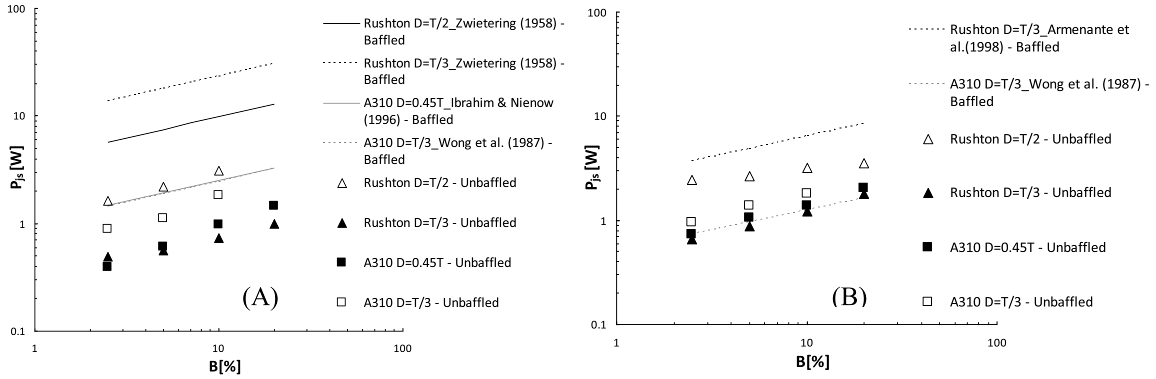

Figure 5: P_{js} values. (A) Configurations with impellers whose C = T/3; (B) Configurations with impellers whose C = T/10

However, the N_{js} parameter does not provide indications on which is the most convenient configuration under the economic view point: it is necessary to couple N_{js} with the corresponding power requirement measurements and use the more suitable P_{js} (power requirements measured at N_{js}) parameter.

The P_{js} values obtained here are shown as symbols in Figures 5A and 5B for the Rushton and A310 impellers respectively. Once again information on the relevant baffled tank behaviour is shown as lines derived from literature correlations.

As regards the larger clearance (C = T/3, Figure 5A), all P_{js} values pertaining the unbaffled configuration are found to be largely lower than those relevant to the tank provided with baffles, with differences up to about an order of magnitude. Also for most cases of low clearance impellers (C = T/10, Figure 5B), the unbaffled configuration appears to be more convenient, though the gap with baffled P_{js} values is largely reduced.

It can be concluded that, as far as particle suspension is concerned, unbaffled vessels may be a much better choice that the more commonly adopted baffled tanks.

As concerns the comparison between Rushton and A310 impellers, the larger A310 impeller is clearly the most convenient in a baffled system, while in the unbaffled vessel, surprisingly enough, the smallest Rushton turbine is found to be comparable with (and even more suitable than) the largest A310, both at T/3 and T/10 clearances.

Finally, by comparing the results shown in Figure 5A and 5B, it can be stated that, amongst the investigated test cases, the adoption of a D = T/3 Rushton impeller offset by C=T/3 from tank bottom guarantees the lowest power consumption for achieving full solids suspension (and consequent full availability for the mass transfer processes taking place in the bioslurry reactor).

It is well known that unbaffled systems are characterized by mixing times significantly larger than those pertaining to baffled systems (Nere et al., 2003). This difference suggests the adoption of baffled tanks for all processes where mixing time is the controlling factor. For bioslurry reactors however this is hardly the case, as for these systems the controlling factor is almost invariably bio-degradation kinetics (which is typically orders of magnitude slower than mixing). Moreover the aerobic processes typically carried out in bioslurry reactors require oxygen to be provided in order to replace that consumed by bioprocesses. This is conveniently obtained in unbaffled tanks by simple contact with air trough the larger and rippled central vortex surface, as well as through the surface of entrained bubbles at sufficiently high speeds (Scargiali et al. 2012). The need for compressed air consumption and for inserting an air sparger in the tank (with related clogging problems), both required by baffled vessels, can therefore be conveniently avoided by adopting an unbaffled vessel. As a matter of fact, the oxygen mass-transfer efficiency of vortexing unbaffled vessels can become as high as that of sparged baffled tanks, and in any case adequate for all bioprocess needs, at sufficiently high agitation speeds (Scargiali et al., 2012). On the basis of all the above considerations, it may be concluded that unbaffled stirred tanks are particularly well suited for bioslurry operations.

4. Conclusions

An unbaffled mechanically stirred bioslurry reactor filled with a mono-dispersed soil and water was investigated from a fluid dynamic point of view. The air presence for aerobic conditions was guaranteed by the vortex formation, typical of uncovered unbaffled stirred tanks. The minimum impeller speed for complete suspension (N_{js}) as well as the relevant power consumption (P_{js}) were measured for different configurations (impeller type, impeller diameter, impeller clearance) of the above system and compared with the corresponding N_{js} and P_{js} values relevant to an identical bioslurry reactor provided with baffles. Results have shown that the aerobic bioremediation of contaminated soils may be conveniently operated in an unbaffled bioslurry reactor stirred by a Rushton turbine with D = T/3 and C = T/3.

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