

# Airlift Bioreactors: Application to Wastewater Treatment

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## Abstract:

After an introductory review, this paper presents a three-phase reactor fluid dynamic model that is used in the development of a generic process for upgrading existing wastewater treatment plants (WWT). The aim is to incorporate nitrification and de-nitrification without additional reactor volume. The core of the process consists of an attached growth airlift reactor (AGAR) in which a biomass carrier is used. Mixing is provided in the aerobic stages by partitions that create an airlift effect. The design procedure for large airlift elements in an aeration basin containing floating solid carriers is based on classic airlift calculation procedures adapted to this specific case. The combination of the organized flow pattern and the low density of the media enable hydraulic prevention of carrier migration between different process stages, eliminating the need of screens. Process performance in a demonstration plant, expressed as airlift liquid velocity, confirms the predicted values within a reasonable range.

## Keywords:

Airlift reactors; wastewater treatment; mathematical model; airlift fluid dynamics

## New reports on use of ALRs for WWT:

Since one of the recognized characteristics of airlift reactors is the potential for scaling up and the relatively low power consumption for agitation and oxygenation, it is only natural that many processes related to wastewater treatment use this type of reactors.

Jin *et al.* (2002) used an airlift reactor in a comprehensive pilot plant system for starch processing wastewater reclamation. The starch was utilized by *Aspergillus oryzae*. Simultaneously to a 95% COD, 93% BOD and 98% suspended solids removal, an important production of  $\alpha$ -amylase (~50 EU/ml) was obtained (Jin *et al.* 1998). An interesting point in this paper is the dependence of fungal morphology on ALR fluid dynamics. In this type of processes, morphology of the fungal biomass is extremely important. Free mycelial growth (wild growth) increases strongly the viscosity, limiting the oxygen transfer rate from the gas to the culture. The solution that has been almost universally adopted for this problem, which attains to citric and other organic acids, antibiotics, etc., is to find the conditions under which the biomass takes the form of fungal pellets. The advantage in gas-liquid transfer rate because of the decrease in viscosity usually overweighs the added resistance stemming from the itraparticle diffusion of oxygen. But the formation of pellets in optimal size and compactness is a very complex matter.

Lazarova *et al.* (1997) studied experimentally the fluid dynamics and the performance for wastewater treatment of a split-vessel airlift with a rectangular section. They studied carefully the influence of suspended solids on gas holdup both in the riser and the downcomer, as well as the influence of the ration of riser to downcomer cross sectional areas on liquid velocity. They compare the experimentally measured velocities for different reactor heights without proposing any correlation. The main aspect stressed by the researchers is the capacity for nitrification observed in various stages.

Many applications of ALR have been reported in processes where the point of interest for researchers interested in ALR and BC is simply that the process, which can take place in a conventional stirred tank, can be run using an ALR as well, with the consequent savings in energy requirements, etc. For example, the use of *Aspergillus niger* for textile wastewater (biological discoloration) was reported by Assadi and Jahangiri (2001). Campos *et al.* used an ALR in a combined (microfiltration and biological) treatment of oilfield wastewater treatment. They obtained satisfactory results in TOC and COD reduction in a continuous process, using an ALR with suspended Polystyrene particles and studying hydraulic retention times from 12 to 48 hours. Both the above-mentioned studies were carried out in small-scale reactors.

Loh and Liu (2001) used an external loop fluidized bed airlift bioreactor for treatment of high strength phenolic wastewater. They used the increase in gas holdup that they get closing a valve in the downcomer and restricting liquid circulation to control in this way the oxygen transfer. The range of variation in their device goes in fact from holdup in an airlift with unrestricted circulation to the holdup in a bubble column, for similar diameters and gas superficial velocity. Obviously, the case of a completely closed valve implies that the downcomer volume is not contributing to the process.

Bakker *et al.*, (1996) immobilized their biomass inside  $\kappa$ -carageenan gel beads, and studied a cascade of two ALRs (small scale) to study the oxidation of nitrite to nitrate by *Nitrobacter agilis*. This is an important step in the nitrification process (*i.e.* the oxidation of ammonia to nitrate via nitrite, usually followed by a denitrification stage with reduction of nitrate to  $N_2$ ). They found advantages in the use of two bioreactors in series, and attributed it to the kinetics of the process (non-competitive substrate and product inhibition). Because the density of the beads was close to unity, there was no problem in fluidizing of the beads in spite of the small scale.

While the basic characteristics of an airlift reactor indicate its fitness for aeration of large volumes of wastewater, the problem of ammonia removal calls for special handling. Two approaches have been lately presented incorporating the nitrification-denitrification element into a basic airlift arrangement. The first one is the biofilm airlift suspension extension reactor (van Benthum 1999-a, 1999-b), which presents the very compact design. The conventional airlift with its three phases in enclosed into an additional vessel (extension) that becomes the anaerobic volume. Part of the liquid and suspended biofilm coated solids overflows the aerobic airlift core and enter the top of the extension, reentering at the bottom. The design allows the control of aerobic/anaerobic times for the biofilm-coated particles suspended in the system in order to improve the nitrification/denitrification of wastewater. The flow of liquid and suspended solids in the extension, which is the anaerobic volume, can be controlled manipulating the overpressure in the headspace of the reactor. A mathematical model was developed and used for the design of a pilot plant. The experimental results of gas and solid holdups concur satisfactorily with the model predictions.

A different approach to the integration of nitrification/denitrification in a wastewater treatment process is the one presented by Shechter *et al.* (2002) that follows.

### The AGAR system:

The AGAR process is used for retrofitting wastewater treatment plants for nitrogen removal and capacity increase, by increasing the quantity and improving the quality of microorganisms in the aeration basin of the biological treatment. The process utilizes shaped plastic carriers for supplying a high surface area on which a bio-film develops. The biomass carriers are mixed in the aeration basin by the air required for supplying the oxygen demand of the aerobic process. Energy cost considerations require that the air supply to the system, one of the major operating costs, be minimized.

The mixing of a high concentration of floating biomass carriers in water requires arrangement of an organized flow pattern, in order to avoid excessive aeration expenses. Airlift hydraulics provides a well organized flow pattern which ensures a liquid velocity sufficiently high to fluidize the plastic carriers in every part of the basin. Since space limitation does not allow to explicit the detailed mathematical expression of the hydraulic model, which will be presented elsewhere (Shechter and Merchuk, 2003), only some results obtained with the model are shown here.

### Simulations:

Figure 1 shows the profiles of gas holdup in the riser, solids holdup in the riser and downcomer, and the superficial velocities of liquid and solid in the riser for a wide range of superficial gas velocity at the inlet of the airlift reactor.

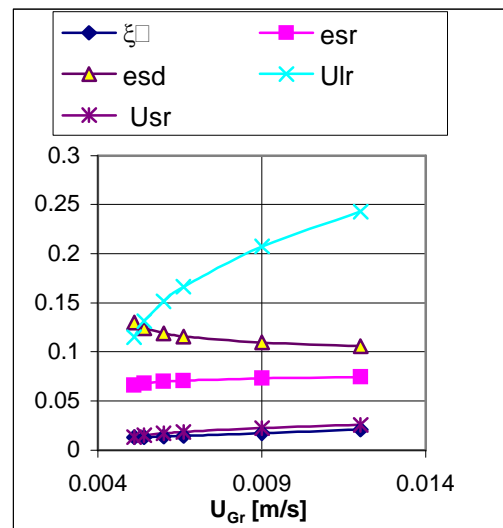


Figure 1: Influence of the gas superficial velocity in the riser ( $U_{Gr}$ ) on the fluid-dynamic variables.

The figure shows that the gas holdup does not change sharply, while the liquid velocity almost doubles itself. The picture is completed by the

profile of solids holdup, which increases in the riser and decreases in the downcomer. The model predicts thus that most of the energy input is related to the movement of the suspended particles.

Figure 2 shows the influence of the total solids load in the system. Again, the variables

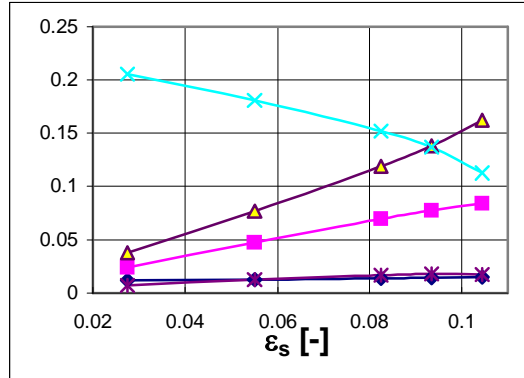


Figure 2: Influence of the solids total loading  $\epsilon_s$  on the fluid-dynamic variables. Legends as in Fig. 1

represented on the graph are gas holdup in the riser, solids holdup in the riser and downcomer, and the superficial velocities of liquid and solid in the riser.

This graph is built for a constant gas input corresponding to a gas superficial velocity of 0.006 [m/s]. While the gas holdup does not change, the liquid velocity drops sharply as the solids holdup both in the riser and the downcomer increase.

Figure 3 shows the influence of the density of the suspended particles on the variables of the process: also in this case the graph is built for a constant gas input corresponding to a gas superficial velocity of 0.006 [m/s].

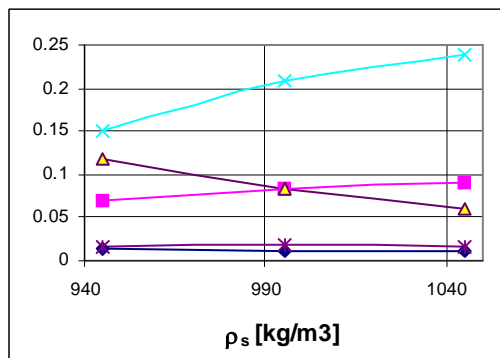


Figure 3: Influence of the density of the suspended solids,  $\rho_s$  on the fluid-dynamic variables. Legend as in Fig. 1.

While the gas holdup in the riser and the velocity of the solids in the riser remain almost constant when the density of the solid changes in 5% under and over the density of water, the solids holdup in the riser and downcomer are affected in opposite ways: while  $\epsilon_{sr}$  increases  $\epsilon_{sd}$

decreases. The lines cross at particle density equal to that of water. The difference between riser and downcomer changes thus from negative to positive as  $\rho_s$  increases. This difference, in absolute terms, is smaller at higher particle density (approximately 0.03 versus 0.074), and the predicted increase in liquid velocity, therefore, concurs with the general conclusions by Heijnen *et al.* (1997). Since in the AGAR system the solids do not move from stage to stage, each stage is, with respect to solid particles, a closed reactor. If the density of the solid is larger than that of the liquid, its rising velocity will be smaller and the holdup of solids in the riser will be larger than in the downcomer, and *vice versa*. The presence of solids, therefore, will always diminish the driving force for circulation, independently of their density, as shown clearly on Fig. 3.

Figure 4 shows the prediction of the model with respect to the influence of the ratio  $A_r/A_d$  on the variables considered, for a constant superficial gas velocity in the riser. As expected, the increase in  $A_r/A_d$  produces an increase in the holdup of solids in the downcomer and a decrease in the liquid velocity in the riser.

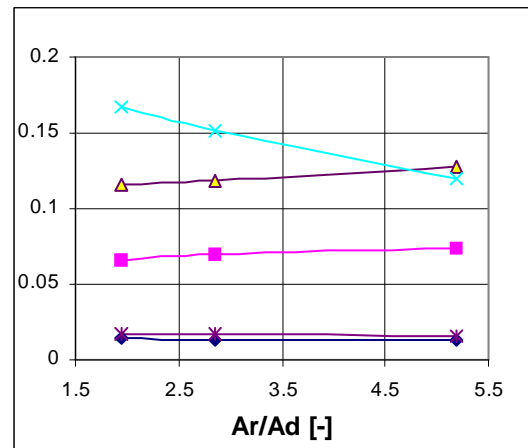


Figure 4: Influence of the riser to downcomer area ratio on the fluid-dynamic variables. Legends as in Fig 1

An interesting point that was observed is that the model would not converge to a result if the gas input was not enough to produce the minimal liquid velocity required for recirculation of solids in the downcomer. This observation was the base for the construction of figure 5, that shows the minimal gas flow rate required to allow the proper circulation of solids in the airlift reactor at each solids loading (shown as: % fill=100\* $\epsilon_s$ /f, where f is the solid volume fraction in a packed bed of particles), for four different densities of the particles. The lines obtained for a constant particle density are straight and the slope increases slightly as the particle density decreases.

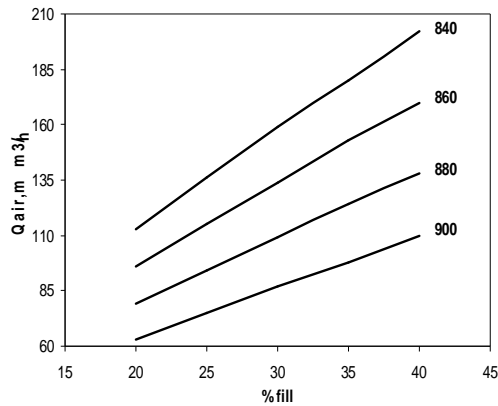


Figure 5: Minimum driving air requirements for different particles fill ratios. The different particle densities are indicated in each line in units of  $[\text{kg}/\text{m}^3]$ .

It is worth noting the strong sensitivity of the model to particle density. The heavier the particle (the closer to water density) the lower the gas flow rate required for the inverse fluidization of the particles in the bed.

**Conclusions:** A mathematical model describing the fluid dynamics of a split vessel, airlift unit of rectangular section in the AGAR process was presented. The model allows the prediction of liquid velocity, gas holdup in the riser, and solids holdup and velocity in both riser and downcomer. The model shows a coherent picture of the behavior of the fluid dynamic system. It was used to predict the minimal gas input rates required for inverse fluidization in the downcomer of the biofilm-carrying solids.

#### Notation:

- A Riser cross-section area, given,  $\text{m}^2$
- A Down-comer cross-section area,  $\text{m}^2$
- A Free passage area for flow from downcomer to riser,  $\text{m}^2$
- f Volume of solids per volume of packed bed of solids, -
- $\varepsilon$  Overall gas holdup
- $\varepsilon_r$  Gas holdup in the riser
- $\varepsilon_d$  Gas holdup in the down-comer
- $\varepsilon_s$  Solids holdup in the riser
- $\varepsilon_s$  solids holdup in the down-comer
- $\rho_l$  Liquid density,  $\text{kg}/\text{m}^3$
- $\rho_s$  Solid density,  $\text{kg}/\text{m}^3$

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