Smart 2003

Advanced Bioprocess Development

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Nitrification of sludge filtrate using expanded bed technology

1. Background

ABD Ltd. is a spin-out company of Manchester Metropolitan University and was incorporated in August 2002. We have developed a low-cost, high-rate, continuous process for nitrification of sludge filtrate, which is based on expanded bed (EB) technology (Figure 1). An expanded bed is formed when liquid is passed up through a bed of particles at a rate such that the upward drag force exceeds the gravitational force and the particles become suspended in the liquid flow. Suspension of particles causes the bed to expand, thus occupying a larger volume, which is proportional to the drag force and, therefore, the upflow velocity.

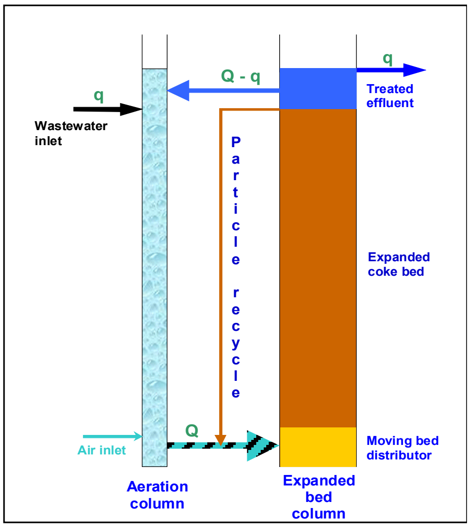


Figure 1: Expanded bed process layout.

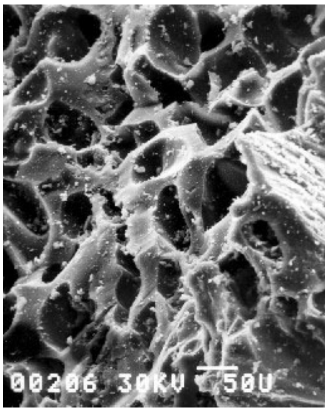


Figure 2: Porous structure of glassy coke as revealed by scanning electron microscope.

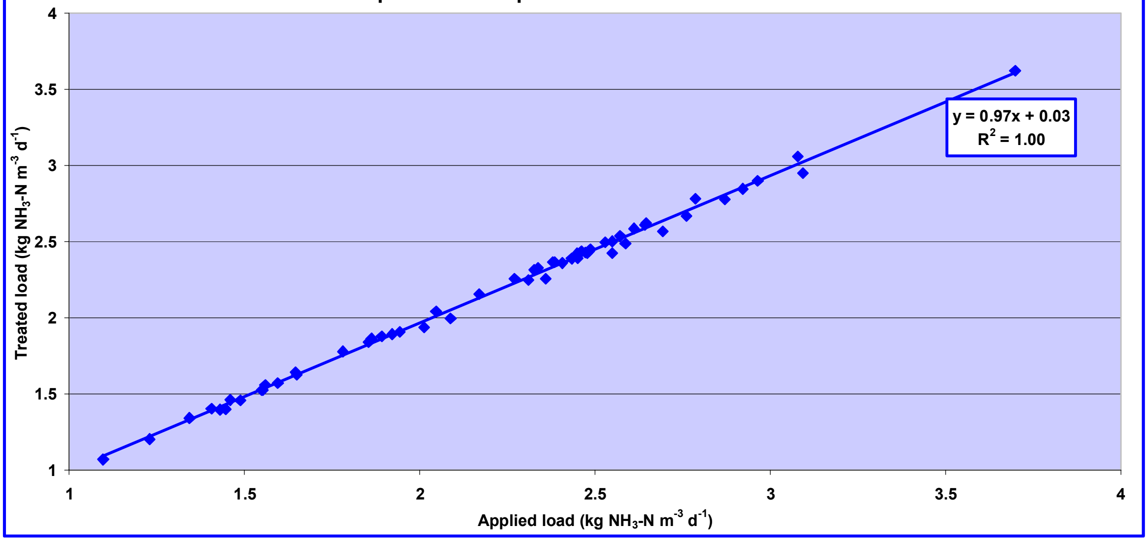
Figure 3: Particulate biofilms (1-2 mm) in expanded bed treating sludge filtrate.

Our technology is a method of process intensification that is based on the natural immobilization of microbes, which grow as biofilms on small particles of glassy coke (Fig. 2) that are retained in the bioreactor. These bioparticles (Fig. 3) provide 1,800 m^2 of superficial surface area per m^3 of expanded bed and it is this huge surface area of active biofilm that lies at the heart of our highly effective bioprocess technology.

Because each particle of coke develops its own biofilm, it is a particulate biofilm system. Since each particle is suspended in the up-flowing wastewater, each particulate biofilm is individually supplied with nutrients (including oxygen) and therefore high rates of mass transfer are achieved. It is the combination of available surface area and high rates of mass transfer that makes our expanded bed processes high-rate, compact and cost-effective.

We nitrified sludge filtrate from a centralised sludge dewatering plant for a period of two years, using a small expanded bed originally developed for tertiary nitrification. The biomass took several weeks to adapt, with heterotrophic bacteria and protozoa decreasing in number and the autotrophic nitrifyers becoming visible dominant (Fig. 3). Once fully adapted, the system was able to oxidise ammonia at high rates (Figure 4). The rates achieved were higher than for tertiary nitrification, owing to an elevated temperature and pH control at the optimum.

Figure 4: Oxidation of ammonia in sludge liquor (reject water) when Expanded Bed operated to achieve > 95% ammonia removal



There are many advantages to our novel process technology:

a. The high biomass concentration and its form (thin biofilms on small particles) results in a high rate of reaction (Fig. 4). This degree of process intensification results in a compact reactor that occupies less space than its competitors, e.g. SBR.

b. Because the bed is expanded, it does not trap solids and thus does not require backflushing. This leads to a simple plant design, which is cheaper to construct and maintain compared to competing processes.

c. Nitrification is an aerobic process and our technology uses a counter-current contactor that has a high rate of oxygen transfer. In pilot-scale trails, we have measured transfer rates of over 20%, which is double that of conventional (co-current) aeration systems. As aeration accounts for 60-65% of the running costs for an aerobic bioprocess, doubling the transfer efficiency should result in an energy saving of at least 30%, making opex significantly lower than for competing processes.

d. Ideally, the nitrified effluent is fed back, either into primary or activated sludge treatment, so that the oxygen content can be used for denitrification. This will also feed nitrifying biomass upstream, thereby augmenting the normal population and increasing the degree of nitrification during secondary treatment.

e. With package plant, units can be factory built, thereby allowing improved quality control and rapid installation.

f. As the process involves growth of microbes as a biofilm, the bed continues to expand. Therefore, biofilm thickness is controlled using automatic particle recycle and re-injection.

2. Process Description

a. Full-scale plants will be similar in general design to that shown in Fig. 1. They will consist of systems for dissolved oxygen (DO) and pH control, together with a counter-current aeration column and an upflow expanded bed column. They will require a recirculation pump, to effect bed expansion and aeration, and a feed pump.

b. Sludge filtrate is pumped into the aeration column, where it mixes with the recirculating wastewater and becomes aerated. The aerated wastewater is pumped to the base of the expanded bed, where it is distributed through a manifold and any inlet turbulence calmed by passage through a moving sand bed ("moving bed distributor"). It then rises through the suspended bioparticles; supplying DO, ammonia and other nutrients to the nitrifying bacteria. Ammonia is oxidised to nitrate and the treated wastewater is discharged through an overflow pipe above the top of the bed, at the same rate that sludge filtrate is fed in. This continuous process can be operated to produce an effluent ammonia concentration below 1 mg/L or it can be specifically chosen to meet the work's discharge requirements.

c. Air is metered into the base of the aeration column at a rate to give a low DO concentration at the top of the bed, using a feedback signal from a DO probe. Recycle of the oxygen-depleted wastewater down through the aeration column whilst N_2-depleted air flows up maximises the oxygen transfer efficiency and minimises the energy consumption. This counter-current gas-liquid contactor is at the heart of our processes' energy efficiency.

d. Alkali is metered into the top of the aeration column according to the pH at the top of the expanded bed. In this way, the acid generated from ammonia oxidation is neutralised and the process can be operated at its optimum pH, thereby maximising the rate of nitrification and minimising the reactor size.

e. Depending on site conditions, temperature control may be required using tank insulation and / or a water jacket. Thus, in hot weather, mechanical heat (from the recirculating pump) and metabolic heat (from the microbes) can be removed and excessive heat loss in cold weather can be prevented. In this way, the process can be operated near its optimum temperature at all times, which also helps to maximise the rate of the process and thus minimise the size of the plant.

f. The ability to vary the air-supply rate according to the DO at the top of the bed means that it is matched to the microbes' oxygen consumption rate. In turn, this rate is controlled by the BOD loading rate (mostly ammonia in sludge filtrate, although any easily-oxidisable organic matter will also be oxidised by heterotrophic bacteria that will grow in the process). In this way, the microbes are effectively fed oxygen "on demand", which minimises the supply of DO and thus further helps to minimise energy consumption.

g. Control of biofilm thickness, and therefore control of expanded bed height, is achieved through bioparticle recycle *via* an injector. The recirculation pump is used to drive the injector, which otherwise has no moving parts. The induced flow through the injector automatically draws wastewater slowly through this internal recycle. Once the bed expands to the level of the particle recycle port, biofilm-coated particles are drawn by the liquid flow to the base of the bed. During passage through the injector and moving bed distributor, excess biofilm is stripped off. Fortuitously, it is the particles with the thickest biofilm that migrate to the top of the bed and are stripped. As the thickest biofilms are the oldest or the most diffusion-limited, the biofilm is controlled to be thin and highly active.

h. Most solids entering the bed are consumed by protozoa or rotifers. Solids shed from the bed are mainly detached biofilm, some of which will be consumed by the protozoa or other organisms within the process. The solids that leave the bed tend to be sloughed biofilm, which is relatively dense and compact and therefore settles rapidly. If the nitrified effluent is returned to the head of the works, these solids will settle out during primary sedimentation. Alternatively, it may be better to feed this effluent into the activated sludge process, where some denitrification should occur if the zone where it is fed is un-aerated. Furthermore, the nitrifyers shed from the expanded bed will augment the small nitrifyer population in the activated sludge, leading to improved nitrification during secondary treatment because of bioaugmentation.

i. By returning the nitrified effluent to an upstream process (primary sedimentation, first activated sludge cell or *via* the activated sludge return line), where some easily-oxidisable organic matter is present but dissolved oxygen is limited, some denitrification will occur. In this way, the total nitrogen content of the works effluent can be reduced, thereby contributing to nutrient (nitrogen) removal targets.

3. Process Performance

a. As mentioned previously, sludge filtrate from a centralised sludge dewatering plant was treated using our expanded bed nitrification process for two years. We found that the process easily achieved an ammonia oxidation rate of up to 3 kg NH_3-N $m^{-3}_{\text{expanded bed}}$ d^{-1} (Figure 4). However, in order to consistently achieve an effluent ammonia concentration of < 10 mg dm^{-3} under plant conditions, we recommend a maximum oxidation rate of 2 kg NH_3-N $m^{-3}_{\text{expanded bed}}$ d^{-1}.

b. Sodium hydroxide (NaOH) or other suitable alkali can be used to neutralise the acid generated from the oxidation of ammonia. Whilst we have calculated that 5.7 kg NaOH should be required per 1.0 kg NH_3-N oxidised, we found that the sludge filtrate had some buffering capacity and that only 5 kg NaOH was required per kg NH_3-N oxidised. We assume that other sludge filtrates (reject waters) will have a similar buffering capacity.

c. Although we did not have the facility to control the DO concentration in the small reactor, we are confident that a dissolved supply of 5 kg O_2 per kg NH_3-N oxidised to nitrate will be sufficient, unless the sludge filtrate contains significantly more easily oxidisable organic matter than material that we have been using from the centralised sludge dewatering plant.

4. Nitrification

a. Nitrification is the biological oxidation of ammonia to nitrate *via* nitrite using naturally-occurring, specialised bacteria called nitrifyers. There are two groups of nitrifyers, whose oxidation reactions are used to extract chemical energy to fuel their metabolism:

   i. ammonia oxidisers, e.g. *Nitrosomonas*, $NH_4^+ + 1½O_2 = NO_2^- + 2H^+ + H_2O$; and

   ii. nitrite oxidisers, e.g. *Nitrobacter*, $NO_2^- + ½O_2 = NO_3^-$.

b. Clearly, nitrification consumes oxygen and generates acid (H^+). Theoretically, in terms of oxygen demand, each 1.0 kg NH_4^+-N requires 4.6 kg O_2. However, additional oxygen is required for consumption of stored carbon by nitrifyers or nitrifyer biomass by protozoa (0.05 kg O_2 per kg NH_3-N oxidised) plus for metabolism of any easily-oxidisable organic matter in the sludge filtrate by heterotrophic bacteria, which will be site specific.

c. Because oxidation of ammonia releases acid, unless the pH is controlled by adding alkali (e.g. sodium hydroxide, NaOH) it will fall to about pH 5 and the process will stop. Theoretically, each 1.0 kg of NH_3-N oxidised requires 5.7 kg NaOH to neutralise the acid released.

d. Like green plants, nitrifying bacteria are autotrophic. That is, they use metabolic energy to convert CO_2 into organic matter (biomass or storage compounds). To extract sufficient energy to fix one molecule of CO_2, an ammonia oxidiser must convert 35 molecules of NH_3 (ammonia) to NO_2^- (nitrite); whilst a nitrite oxidiser must convert 100 molecules of NO_2^- to NO_3^- (nitrate). Therefore, there is normally sufficient CO_2 in sludge filtrate (as carbonic acid, carbonate or bicarbonate - depending on pH) to meet the carbon requirements of the nitrifyers. Overall, 25 NH_3 molecules must be oxidised to fix one CO_2 molecule into biomass.

5. Patent protection

a. US6572773 Nitrification process

b. WO03033411 Improvements in and relating to fluid bed expansion and fluidisation