Nitrification of secondary effluent 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 secondary effluent, 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.

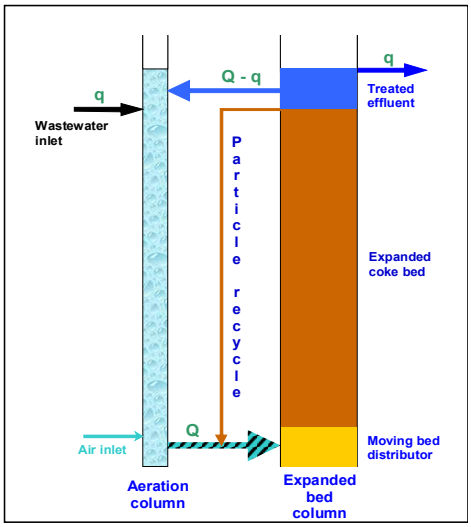


Figure 2: Porous structure of glassy coke as revealed by scanning electron microscope.

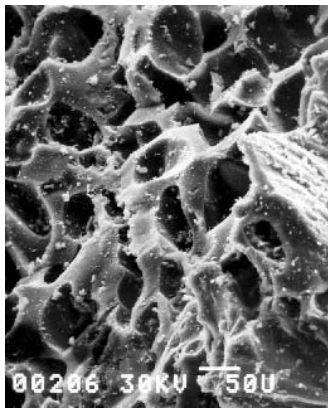
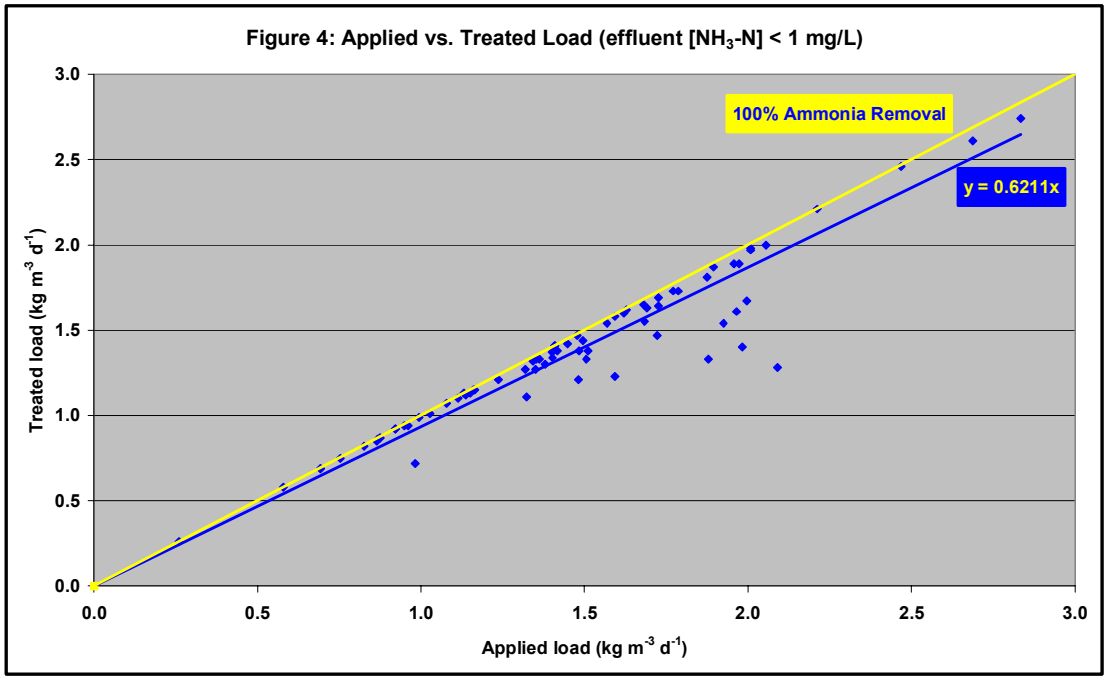


Figure 3: Particulate biofilms (1-2 mm) in expanded bed treating activated sludge final effluent.

Our technology is a method of process intensification that is based on the natural immobilization of microbes that grow as biofilms on small particles of glassy coke (Fig. 2) and 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 massive 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 have been nitrifying activated sludge final effluent at a large, mixed domestic and industrial wastewater treatment plant since November 2001, using a small expanded bed. We have now developed the process to pilot-scale for tertiary nitrification. The system is able to oxidise ammonia at high rates (Figure 4) and the next step is to demonstrate the technology at full-scale. We propose to determine the maximum sustainable rate that can be achieved at full-scale with an on-site trial, based on scale-up of our pilot plant.



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, e.g. a BAFF plant would be 4 times bigger.

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. The fact that backflushing is not necessary also allows a complex community of organisms to develop that, although dominated by nitrifying bacteria, includes heterotrophic bacteria, protozoa, rotifers, nematode and oligochaete worms. This complex community is able to oxidise residual organic matter (cBOD) in the secondary effluent, as well as consume suspended solids. Therefore, despite solids entering and solids being generated in the process, the effluent concentration of cBOD and SS is lower than the influent by > 50%.

d. 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.

e. Our pilot plant has recently been retro-fitted with a novel inlet manifold, which has 64 outlets (equivalent to 320 m^{-2}). This replaced a single outlet and has significantly improved the distribution of the inlet flow. The manufacturers of the device have successfully built similar manifolds up to 6 m in diameter, thereby providing a proven scale-up route. Our technology can therefore be built at a range of scales to suit the market. With smaller 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. A full-scale plant will be similar in design to that shown in Fig. 1. It will consist of a system for dissolved oxygen (DO) control, together with a counter-current aeration column and an upflow expanded bed column. It will require a recirculation pump, to provide the energy for bed expansion and aeration, and a secondary effluent feed pump (site specific).

b. Secondary effluent is pumped (or gravity fed) 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 secondary effluent is fed in. This continuous process can be operated to produce an effluent ammonia concentration specifically chosen to meet the work's requirements, down to 1 mg/L.

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. 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 secondary effluent, although any easily-oxidisable organic matter will also be oxidised by heterotrophic bacteria). 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.

e. 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 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 through with the liquid flow and are re-injected into 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 thickness is controlled and nutrients are supplied throughout the biofilm, so keeping the cells metabolically active.

f. Most solids entering the bed are consumed by protozoa, rotifers, and nematode or oligochaete worms. Solids shed from the bed are mainly detached biofilm, some of which will be consumed by the organisms within the process. Solids leaving the bed tend to be sloughed biofilm, which is relatively dense and compact and thus settles rapidly. The need for post-sedimentation is largely eliminated as these solids are suitable for separation with e.g. a hydrocyclone. Alternatively, the treated effluent can be membrane filtered, e.g. to achieve disinfection. Because the expanded bed is able to remove > 80% of incoming bacteria by the actions of filter-feeding protozoa and rotifers, the surface area of membrane required is reduced compared to those processes where the bacterial concentration is much higher. This is another significant advantage of our process technology.

3. Process Performance

a. As mentioned previously, activated sludge final effluent (ASFE) was treated using our small expanded bed nitrification process from November 2001 until November 2003, when it was adapted to sludge liquor (reject water) treatment. Because this process was operated experimentally and we varied operational conditions to explore process latitude, many data points are not relevant to how the process would be used in practice. When operated to produce < 1 mg dm^{-3} NH_3-N in the effluent, we could achieve 100% ammonia removal at oxidation rates up to 2.5 kg NH_3-N $m^{-3}_{expanded\ bed}$ d^{-1} (Figure 4). However, in order to consistently achieve an effluent ammonia concentration of < 1 mg dm^{-3} under plant conditions, we recommend a maximum oxidation rate of 1.0 kg NH_3-N $m^{-3}_{expanded\ bed}$ d^{-1}.

b. We have successfully operated at pilot-scale since late 2003 and we are confident that a full-scale system based on this pilot plant design will be suitable for nitrification of any works' secondary effluent.

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. The oxygen consumption for nitrification equates to 4.6 kg O_2 per 1.0 kg NH_4^+-N oxidised. Additional oxygen is required for respiration of stored carbon by nitrifyers, as well as respiration by heterotrophic bacteria and protozoa, rotifers, nematode and oligochaete worms that consume any cBOD and SS in the secondary effluent or consumption of biofilm and SS generated in the process (all site specific).

c. 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 35 molecules of NO_2^- (nitrite); whilst a nitrite oxidiser must convert 100 molecules of NO_2^- to 100 molecules of NO_3^- (nitrate). Because of this low energy yield, there is normally sufficient CO_2 in secondary effluent (normally as bicarbonate, HCO_3^-) to meet the carbon requirements of the nitrifyers. Overall, 25 NH_3 molecules must be fully oxidised to fix 1 CO_2 molecule into biomass.

5. Patent protection

a. US6572773 Nitrification process

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