High rate treatment by aerobic upflow sludge blanket (AUSB) with external oxygenation

K.R. Sharma and J.C. Huang

Department of Civil Engineering, The Hong Kong University of Science and Technology, Clearwater Bay, Kowloon, Hong Kong

Abstract A 3-year study was conducted using an aerobic upflow sludge blanket (AUSB) reactor to achieve high-rate biological treatment through maintenance of a high biomass concentration (7–10 g VSS/L) together with a high oxygen flux. The AUSB reactor was not aerated directly; instead, oxygenation was provided in an external chamber with flow recirculation. The oxygenation was provided at four different pressurizations: 0, 15, 20 and 25 psig. The AUSB reactor was also pressurized to avoid the flotation of biomass. The flow recirculation rate was varied from 400% to 1,500% in order to ensure adequate oxygen supply. It was found that the AUSB system was able to handle a volumetric loading of as high as 10 kg COD/m^3-day with a removal efficiency of 92%. Despite a high upflow velocity through AUSB, the effluent suspended solid concentration was mostly below 60 mg/L. The active fraction of biomass in the AUSB sludge was about 3 times higher than that of the regular activated sludge. This was indicated by a very high specific oxygen uptake rate (SOUR), up to 180–250 mg O_2/g VSS-hr. The sludge yield in the entire system was only 0.09 to 0.13 g VSS/g COD removed. This was mainly caused by additional auto-oxidation of bio-solids in the oxygenation chamber due to flow recirculation.

Keywords Aerobic upflow; external oxygenation; flow recirculation; high biomass level; high-rate wastewater treatment; pressurized reactor; sludge blanket (AUSB)

Introduction

Despite its popularity in treating municipal as well as industrial wastewater, the activated sludge process has some inherent disadvantages such as high sludge production and low volumetric loading capacity due to its low biomass level in the aeration tank. Because of the low volumetric loading, an activated sludge plant requires a large land area for its reactor and the solid-liquid separation unit. In an effort to overcome this problem, several new treatment processes, mainly based on maintaining a high biomass concentration and increasing oxygen transfer rates in the reactor, have been developed. An increase in biomass level can be achieved by maintaining biomass growth in the form of biofilm or sludge aggregates, whereas better oxygen transfer rates can be achieved by using pure oxygen or pressurized aeration/oxygenation. Recently, the aerobic upflow sludge blanket (AUSB) process, which incorporates some of these features, has been developed (Mishima and Nakamura, 1991). In addition to maintaining a high biomass concentration, the AUSB process is operated at a low hydraulic retention time (HRT), high upflow velocity, and high organic loading rate. The low HRT and high upflow velocity promote the growth of well settling large sludge aggregates (Tijhuis *et al*., 1994; Wirtz and Dague, 1996), while high organic loading ensures sufficient new biomass growth (Wirtz and Dague, 1996).

The AUSB process is reported to offer a high biomass retention, good solid-liquid separation and satisfactory treatment performance at high organic loadings (Mishima and Nakamura, 1991; Shin *et al*., 1992). A key feature of this process is that the sludge is subjected to a low mixing shear through the use of external oxygenation to the recirculated effluent. This kind of operating strategy promotes sludge aggregation and also allows most of the produced biomass to be retained in the form of a well-settled sludge blanket.

Water Science and Technology **Vol 50 No 8 pp 193–200**

Consequently, a high biomass concentration can be maintained without a need for a final clarifier, thereby allowing a high volumetric loading. However, the high volumetric loading in such a system must be coupled with an adequate oxygen supply to meet the microbial demand during organic stabilization. This can be achieved by a high effluent recirculation, through which aeration/oxygenation is applied externally. The rate of oxygen supply in such an arrangement depends on both the oxygenated DO in the recirculated flow and the extent of recirculation. Apart from providing enough oxygen, the flow recirculation also helps in maintaining a high upflow velocity necessary to provide a good mixing for substrate transport (Kato *et al*., 1994). Oxygenation under pressure can achieve a much higher DO level so that a high oxygen flux can be maintained with a small effluent recirculation. On the other hand, reducing the pressure during oxygenation and increasing the effluent recirculation can also achieve a similar oxygen supply. It should be noted here that a pressurized AUSB reactor must accompany the pressurized oxygenation to avoid release of air bubbles, thus preventing the flotation of biomass. Obviously, pressurized oxygenation coupled with a pressurized reactor will somewhat complicate the operation of an AUSB system. On the other hand, if oxygenation is done without pressurization, a high effluent recirculation will be needed to supply a given amount of oxygen. This will increase pumping energy and may also result in a substantial sludge washout due to an excessive upflow velocity, thereby reducing biomass retention in the reactor. Thus, a proper balance between pressurization and effluent recirculation should be found to achieve a good treatment performance. That is, the upflow velocity is high enough for sufficient mixing, but not excessively high to washout the biomass. Understanding the performance response under different combinations of pressurization and flow recirculation is, therefore, necessary for the selection of proper operating conditions. Thus, this study was conducted to evaluate the performance of AUSB at a high volumetric loading under different combinations of pressurized oxygenation and effluent recirculation. Results of this study will serve as a basis for selecting proper operating conditions for the AUSB process.

Materials and methods

A schematic of the reactor setup used in this study is presented in Figure 1. The system consisted of two separate components: an AUSB reactor and an external oxygenation chamber. The AUSB reactor having an effective volume of 2.2 L was made of a tapered acrylic cylinder. The purpose of using a tapered reactor was to increase the surface area at the upper region to reduce the upflow velocity to minimize the sludge washout. A high upflow velocity at the bottom was intended to provide a better sludge mixing. Besides the hydraulic mixing, a low speed paddle agitator (3 rpm) along the vertical axis of the reactor was employed. Three sampling ports were provided at different heights of the reactor to facilitate sampling. The oxygenation chamber was made of a translucent acrylic cylinder. A working volume of 2.5 L was maintained by controlling the water level in the chamber. An oxygen generator (AirSep, USA) was used to provide pure oxygen for oxygenation. Peristaltic pumps (Cole Palmer, USA) were used to control both the influent and recirculated effluent flow rates. The influent was injected directly to the reactor, not to the oxygenation chamber. The reactor was seeded with fresh activated sludge obtained from a local sewage treatment plant.

The synthetic wastewater used in this study was similar to that employed by Shin *et al*. (1992), and it contained a mixture of glucose, sodium acetate and yeast extract with a COD ratio of 40:40:20. Other necessary nutrients and trace minerals (Beun *et al*., 1999) were supplemented as required. A stock synthetic wastewater was prepared to have the following compositions: glucose, 5.16 g/L; sodium acetate, 6.41 g/L; yeast extract, 2.19 g/L; NH_4Cl, 0.80 mg/L; K_2HPO_4, 0.31 g/L; KH_2PO_4, 0.13 g/L; $MgCl_2.6H_2O$, 1.10 g/L; $CaCl_2$,

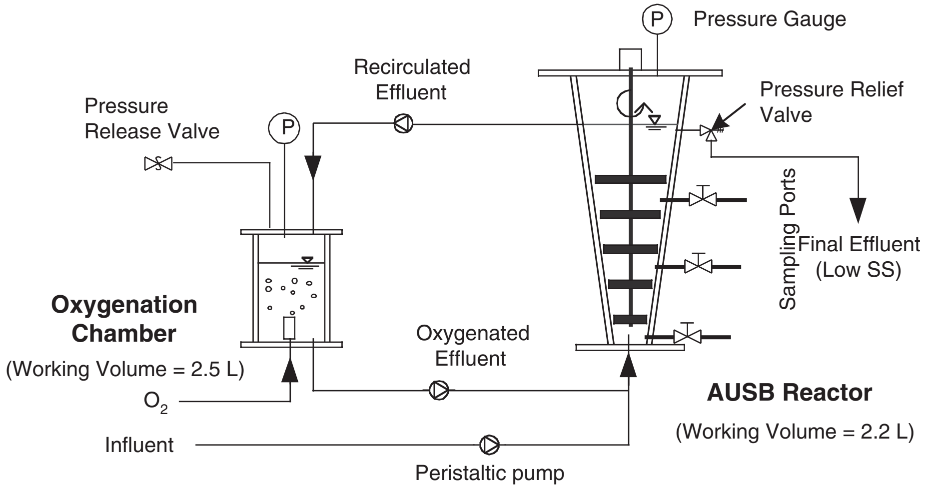

Figure 1 Schematic of the AUSB reactor set-up

1.05 g/L; trace solution, 2.50 mL/L. Total COD of the stock solution was 12,500 mg/L with a COD: N: P ratio of 150:5:1. The compositions of the trace solution were: $FeCl_3.6H_2O$, 15.0 g/L; H_3BO_3, 1.5 g/L; $CuSO_4$, 0.2 g/L; KI, 0.3 g/L; $MnSO_4.H_2O$, 1.0 g/L; $(NH_4)_6Mo_7O_{24}.4H_2O$, 0.4 g/L; $ZnSO_4.7H_2O$, 1.2 g/L; $CoCl_2.6H_2O$, 1.5 g/L; $C_6H_5Na_3O_7.2H_2O$, 10.0 g/L. The stock solution was prepared regularly and stored at 4°C. Depending upon the intended influent COD, the stock solution was diluted with tap water before injecting it into the reactor. For pH buffering, $NaHCO_3$ was added to the substrate.

A large flow recirculation was used to maintain an adequate oxygen supply rate, which also provided sufficient mixing of the sludge bed. Oxygenation of recirculated flow was carried out at 0, 15, 20, and 25 psig pressures in different test runs. To avoid release of gas bubbles and resulting sludge floatation, the AUSB reactor was also pressurized to the same level as the oxygenation chamber. The DO level at the reactor's inlet was found to vary from 22 to 68 mg/L at pressurized oxygenation of 0 to 25 psig. The flow recirculation rate was adjusted based on the required oxygen supply under each operating condition. As a result, the recirculated flow rate was also varied from 4.4 L/h at 25 psig to 14 L/h at 0 psig, while the influent flow rate was maintained at 1.1 L/h, which was equivalent to 2-h hydraulic retention time (HRT) based on the influent flow. The maximum organic loading rate was 3.8 kg TOC/m^3-day (equivalent to 10 kg COD/m^3-day). The system was operated at 30 ± 1°C in an environmental chamber. The operating conditions under various experimental runs are summarized in Table 1.

The total organic carbon (TOC) concentrations in both the influent and the filtered effluent samples were analyzed with a TOC analyzer (SHIMADZU model TOC–700A and

Table 1 Summary of the operating conditions under different experimental runs

Test run →	**1**	**2**	**3**	**4**
Operating pressure (psig)	0	15	20	25
Influent flow rate (L/h)	1.1	1.1	1.1	1.1
HRT (h)	2.0	2.0	2.0	2.0
Feed DO (mg/L)	22–29	35–50	38–63	49–68
Recirculated flow rate (L/h)	7–15	11	10–11	4.4–6.6
Recirculation ratio	6–13	10	9–10	4–6
Liquid upflow velocity^{+} (m/h)	1.0–12.8	1.5–9.6	1.4–9.6	0.7–6.1

$^{+}$ lowest at the top and highest at the bottom of the reactor also SHIMADZU model TOC-V CPH). In order to establish a correlation between TOC and COD, the influent COD was measured frequently using a Hach kit. From the measurements, a conversion factor of 2.65 was obtained, which could be used to convert TOC to COD for reference purposes. Dissolved oxygen (DO) was measured with a DO meter (YSI Model 58). Since the instrument was unable to measure a DO higher than 20 mg/L, sample dilution was required for high DO measurement. Determinations of suspended solids (SS), volatile suspended solids (VSS), and specific oxygen uptake rate (SOUR) were carried out according to the Standard Methods (1998).

Results and discussion

The system was operated at four different pressurizations (0, 15, 20, and 25 psig), in different test runs. An increase in pressurization always resulted in a higher level of oxygenation, thereby making it possible to reduce the flow recirculation. Thus, an increase in operating pressure was accompanied by a reduced flow recirculation rate. The following discussion summarizes the combined effects of pressurization (or feed DO level) and the flow recirculation on the treatment performance in each specific test run.

Treatment performance

The influent and effluent TOC and DO levels at the inlet and outlet of AUSB for two typical test runs (at 0 and 20 psig) are shown in Figure 2. The influent TOC in each test run was increased to a maximum level of 296 to 318 mg/L in steps. At the highest influent TOC, the corresponding volumetric loading rate was 3.6–3.8 kg TOC/m^3-day (9.5–10.1 kg COD/m^3-day). The step-wise increase in influent TOC was intended to assess the system's response at different loading levels. The cumulative TOC removal (both for the system overall and for AUSB alone) and cumulative oxygen consumption in AUSB for the two test runs are also shown in Figure 2. Both the TOC removal and the oxygen consumption rates for each test run could be obtained from the slopes of the corresponding linear plots.

The performance results at the highest loading of the four test runs are summarized in Table 2. The TOC removal efficiencies were above 90% at pressurizations of up to 20 psig. However, the efficiency decreased to 84% when the system was operated at 25 psig pressure. A comparison of TOC removal rates against oxygen consumption is also shown in Table 2. The oxygen utilization coefficient, which is defined as the oxygen consumption per unit COD removed in the AUSB reactor, was used to compare the effectiveness of the system in utilizing oxygen to remove organic matter. It should be noted here that, since oxygenation of the recirculated flow was accomplished in an external oxygenation chamber, a portion of TOC could also be removed there. Thus, the TOC removal by AUSB was lower than that by the entire system. However, the extent of TOC removal by the oxygenation chamber varied with the operating conditions as shown in Table 2. The TOC removal by the AUSB should be used to describe the characteristics of the reactor.

The rate of TOC removal by AUSB was the highest (7.66 kg COD/m^3-day) at 20 psig. The corresponding oxygen consumption rate was 4.35 kg O_2/m^3-day. Both values decreased significantly when the pressure was increased to 25 psig, which had a reduced recirculation rate. However, the oxygen consumption rate did not change as much as the substrate removal rate under such an increase of pressurization. Two possible reasons to account for the reduction of treatment performance at 25 psig pressure are: inhibition of bioactivity at a higher pressure, and poor sludge mixing due to a lower flow recirculation rate. During this test run, when the loading was increased from a low to the highest rate of 3.8 kg TOC/m^3-day, the recirculation rate was also increased from 4.4 to 6.6 L/h. With such an increase in recirculation, no change in the TOC removal was observed for the AUSB reactor. This indicated that the lower substrate removal observed at 25 psig pressure was probably due to bioactivity inhibition at such a high pressure, not due to low flow recirculation. Unfortunately, the effect of pressurization beyond 25 psig was not studied because the reactor was not designed to take a higher pressure. When the pressurization was lower than 20 psig (i.e., 15 and 0 psig), an increase of flow recirculation was required to obtain the same oxygen supply rate. At the same time, it was observed that both the substrate removal and the oxygen consumption rates were somewhat reduced. However, the magnitudes of reduction were smaller than that observed when the pressure was increased to 25 psig. The lower substrate removal at a lower pressurization was apparently caused by a lower inlet DO, which reduced oxygen penetration into the sludge flocs.

As shown in Table 2, an increase in oxygen utilization coefficient (oxygen consumption per unit COD removed in AUSB) was observed with increasing operating pressure and hence, the inlet DO. Theoretically, a high oxygen utilization coefficient would indicate a higher rate of endogenous respiration, and hence lower sludge production. A low coefficient would indicate a larger fraction of COD being used for synthesis, and a higher sludge production rate. Despite the increase in oxygen utilization coefficient with pressurization, the biomass yield coefficients in the four test runs with different operating conditions were comparable, and these will be discussed later.

A high substrate removal rate could be achieved in AUSB due to its high biomass concentration and also a higher fraction of active biomass. The sludge bed was found to consist of large sludge aggregates with a gummy nature, which formed an effective filter matrix. Thus, despite the high upflow velocity, the AUSB was able to retain biomass at a higher concentration (7–10 g VSS/L), which was about five times higher than that in an activated sludge process. The biomass activity was measured by conducting a series of specific oxygen uptake rate (SOUR) tests. For this purpose, sludge samples were collected from three sampling ports at different reactor heights. Diluted sludge samples with a VSS concentration of about 200 mg/L were used in the SOUR determination, while the initial COD was

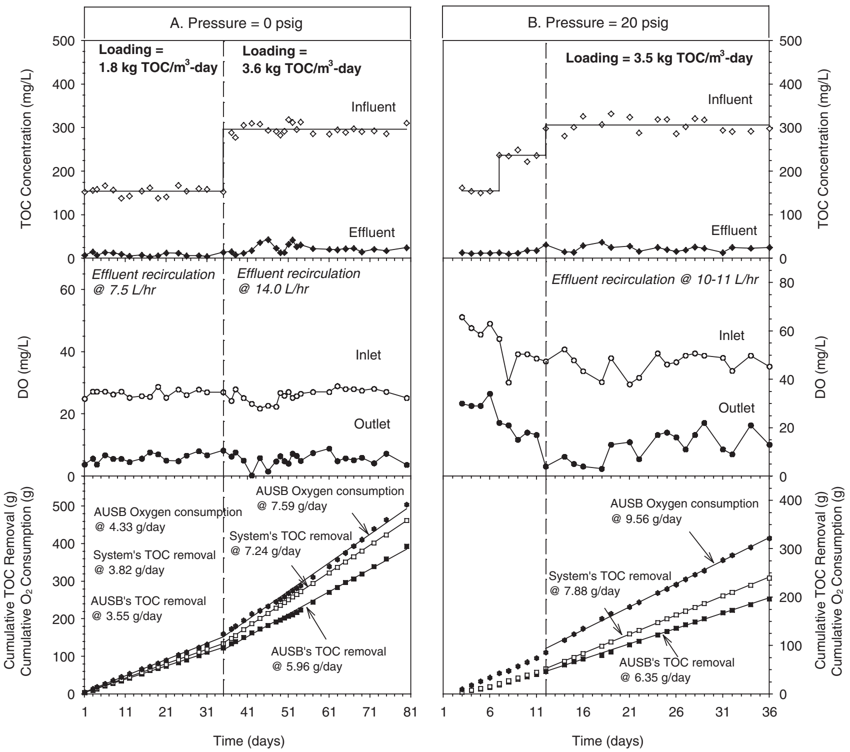

Figure 2 Typical performance results (A) at 0 psig (B) at 20 psig

Table 2 Performance results at different pressurizations and recirculations

Parameters	Test runs 1	2	3	4
Operating pressure	0 psig	15 psig	20 psig	25 psig
Influent flow rate (L/h)	1.1	1.1	1.1	1.1
Flow recirculation (%)	1,300	1,000	950	600
Inlet DO (mg/L)	22–29	35–50	38–52	49–59
Outlet (mg/L)	0–9	6–19	3–22	0–14
Average influent TOC (mg/L)	296	305	305	318
Effluent TOC (mg/L)	22.6 ± 9.4	27.8 ± 9.2	22.8 ± 6.5	49.3 ± 9.2
TOC Removal %	92.4 ± 3.0	90.6 ± 2.1	92.6 ± 2.0	84.5 ± 2.8
Average organic loading rate				
kg TOC/m^3-day (kg COD/m^3-day)	3.59 (9.5)	3.74 (9.9)	3.83 (10.1)	3.60 (9.5)
Organic removal rate				
kg TOC/m^3-day (kg COD/m^3-day)				
System overall:	3.29 (8.7)	3.34 (8.8)	3.58 (9.5)	3.08 (8.2)
In AUSB only:	2.71 (7.2)	2.60 (6.9)	2.89 (7.7)	2.25 (6.0)
TOC removal in oxygenation chamber (%)	17.6	22.2	19.3	26.9
AUSB oxygen consumption				
kg O_2/m^3-day	3.45	3.94	4.35	3.95
kg O_2 consumed/kg COD removed	0.48	0.57	0.57	0.66

kept at 1,000 mg/L. The test was conducted at 30°C. The AUSB sludge bed showed a high SOUR of up to 180–250 mg O_2/g VSS-hr, which was three to four times higher than that of the normal activated sludge. It must be noted that these values were obtained under a condition which had a low VSS and a high mixing intensity. Thus, neither substrate nor DO was limiting; as such, the biomass was able to exert its maximum activity. On the other hand, inside the AUSB reactor, the VSS level was as high as 7–10 g VSS/L. Under such a high biomass level and a low mixing intensity, penetrations of substrate and DO into the sludge aggregates could become limiting. Thus, the actual oxygen uptake rate inside the AUSB reactor was much lower than the values indicated here. It is also worth pointing out that a higher SOUR suggested a greater fraction of active biomass in the sludge bed. This suggestion was verified by the high values of the endogenous SOUR, which were observed for the sludge taken from the bottom of the sludge bed. To make SOUR measurements, a withdrawn sludge sample was first aerated continuously without adding any substrate. During the course of aeration, the sludge SOUR was measured frequently until a stable value representing the endogenous SOUR was obtained. After several measurements, the endogenous SOUR was found to vary from 13 to 20 mg O_2/g VSS-hr, which was two to three times higher than those normally observed for the activated sludge system. The higher fraction of active biomass in AUSB was mainly caused by a high DO in the reactor, which allowed oxygen to penetrate deeper into the sludge aggregates.

Effect of organic loading rate on TOC removal

The TOC removal rates in AUSB at different volumetric loading rates are presented in Figure 3. At a loading rate of below 3.4 kg TOC/m^3-day, the volumetric TOC removal rate increased almost linearly with the loading. Beyond that, very little further increase in TOC removal rate was observed. This indicated that the TOC removal at a higher loading rate was limited by the microbial reaction rate, due to either substrate transport limitation or microbial activity. It must be noted here that the maximum loading capacity of 3.4 kg TOC/m^3-day is applicable to the laboratory scale AUSB reactor used in this study, in which the inlet flow distribution was not optimum because of a smaller flow rate. In full scale

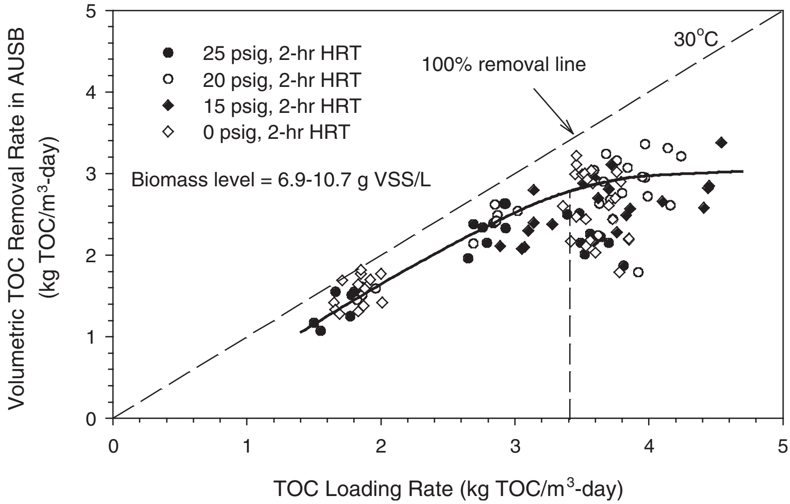

Figure 3 Effect of loading on substrate removal rate

application, a higher loading capacity could be realized by providing a better feed distribution, which would enhance sludge mixing and mass transfer in the reactor.

Sludge washout and biomass yield

During the entire study, the effluent SS was generally below 60 mg/L and its average ranged from 41 to 45 mg/L. Considering that the reactor was operated at very high hydraulic and organic loading rates, the low levels of effluent SS reflected that AUSB was extremely effective in retaining the produced biomass. Obviously, upon an extended period of operation, there would be a need for periodic wasting of the sludge from the reactor. Based on the volume of the collected effluent and the measured SS and VSS concentrations, the average sludge washout rate for each test run could be computed from the cumulative washout of biomass. In addition to the washout through effluent discharge, some excess sludge was also wasted occasionally. The sludge wasting rate, which included both the effluent washout and the intentional sludge wastage, was then calculated for each test run. The total amount of biomass produced in each test run was taken as the sum of the total biomass gain in the reactor and the total biomass wastage. The observed biomass yield was then estimated as the ratio of the total biomass produced to the total TOC (or equivalent COD) removed. The observed biomass yield ranged from 0.09 to 0.12 g VSS/g COD removed at different test runs, and these were significantly lower that the normal biomass yield in an activated sludge process. In two separate test runs (data not shown) conducted without flow recirculation, the observed biomass yields varied from 0.31 g VSS/g COD removed at 0.5-h HRT to 0.46 g VSS/g COD removed at 0.2-h HRT, which were significantly higher than the observed yields with flow recirculation. Thus, the observed lower yields were most likely caused by the continuous auto-oxidation of biomass, which was carried over with the recirculated flow to the oxygenation chamber. The high DO level in the oxygenation chamber allowed the biomass to undergo auto-oxidation at its maximum rate. This together with a high effluent recirculation resulted in a very low sludge yield.

Conclusions and perspectives

The performance results showed that the AUSB process was able to achieve good substrate removal at different operating conditions. The AUSB process was able to treat organic wastewater with a volumetric loading rate of as high as 3.8 kg TOC/m^3-day, which was equivalent to 10 kg COD/m^3-day. This represents a 5 to 10 times higher loading rate as compared to the normal activated sludge process (about 1–2 kg COD/m^3-day). The high loading rate was achievable due to the high biomass level in the reactor (7–10 g VSS/L) and a higher fraction of active biomass, which was reflected by a high biomass SOUR (180–250 mg O_2/g VSS-hr). Despite the high upflow velocity through the reactor, the biomass washout was not significant. The suspended solids concentration in the effluent was mostly below 60 mg/L. This type of effluent could be polished by a micro-screener or sand filter for further removal of suspended solids without a need for a secondary clarifier. The sludge yield in the AUSB system (0.09 to 0.12 g VSS/g COD) was much lower than the conventional activated sludge process. The low sludge yield was mainly caused by "enhanced auto-oxidation" of bio-solids in the oxygenation chamber, which had a very high DO and provided 10–30 minute HRT. The results demonstrated that the AUSB process can be used for high rate wastewater treatment. The process provides a promising new alternative in situations where land availability is severely limited.

References

APHA, AWWA, WPCF (1998). *Standard Methods for the Examination of Water and Wastewater*, *20th Edition*. Washington DC, USA.

Beun, J.J., Hendriks, A., van Loosdrecht, M.C.M., Morgenroth, E., Wilderer, P.A. and Heijnen, J.J. (1999). Aerobic granulation in a sequencing batch reactor. *Wat. Res.*, **33**(10), 2283–2290.

Kato, M.T., Field, J.A., Versteeg, P. and Lettinga, G. (1994). Feasibility of expanded bed granular sludge bed reactors for the anaerobic treatment of low-strength soluble wastewaters. *Biotechnol. Bioeng.*, **44**, 469–479.

Mishima, K. and Nakamura, M. (1991). Self-immobilization of aerobic activated sludge: A pilot study of the Aerobic Upflow Sludge Blanket process in municipal sewage treatment. *Wat. Sci. Tech.*, **23**(4–6), 981–990.

Shin, H.S., Lim, K.H. and Park, H.S. (1992). Effect of shear stress on granulation in oxygen aerobic upflow sludge bed reactors. *Wat. Sci. Tech.*, **26**(3–4), 601–605.

Tijhuis, L., van Loosdrecht, M.C.M. and Heijnen, J.J. (1994). Formation and growth of heterotrophic aerobic biofilms on small suspended particles in airlift reactors. *Biotechnol. Bioeng.*, **44**, 595–608.

Wirtz, R. and Dague, R. (1996). Enhancement of granulation and start-up in the anaerobic sequencing batch reactor. *Wat. Environ. Res.*, **68**, 883–892.