Journal of Industrial and Engineering Chemistry 31 (2015) 257–262

Contents lists available at ScienceDirect

Journal of Industrial and Engineering Chemistry

journal homepage: www.elsevier.com/locate/jiec

# Influence of carbon/nitrogen ratio and non-aerated zone size on performance and energy efficiency of a partially-aerated submerged fixed-film bioreactor

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ARTICLE INFO

*Article history:*
Received 1 September 2014
Received in revised form 4 May 2015
Accepted 25 June 2015
Available online 9 July 2015

*Keywords:*
Partially-aerated submerged fixed-film bioreactor
Non-aerated zone size
COD removal
Nitrogen removal
Energy performance coefficient

ABSTRACT

Performance and energy efficiency of an upflow partially aerated submerged fixed-film (UP/ASFF) bioreactor was evaluated during a 10-month operation period. Increasing loading rates at constant HRT and COD/N increased nitrogen removals. Increase of non-aerated zone could also improve the nitrogen removals up to 83%. Energy performance coefficient based on required electrical energy showed that the energy efficiency of the system increases at lower COD/N value and bigger non-aerated zone for simultaneous COD and nitrogen removal from the synthetic wastewater. The present study showed also similar performance for municipal wastewater, demonstrating the potential of UP/ASFF system to treat high-ammonium municipal wastewaters.

## Introduction

Reuse of treated wastewater has recently attracted increasing attention due to global population growth particularly in urban societies and excessive consumption of resources in different countries [1]. Predominant municipal wastewater pollutants include organic matters and nitrogen in ammonium state [2]. Excessive presence of the nutrients in wastewater has caused serious natural alterations such as eutrophication, resulting in undesirable quality of water for other utilization [3]. The feasibility of applying ASFF system in the treatment of various wastewaters has been demonstrated without some of the problems of activated sludge process in many studies. The system is consisted of three phases: a solid phase acting as the support media (basalt, clay, PVC, etc.) for microbial attachment and growth, liquid phase where the support media is submerged, and gas phase which is provided by the inlet air into the bioreactor [4–6]. The ASFF treatment systems have many advantages such as small footprints, low cost, high sludge retention time which leads to grow nitrifying bacteria [7], ability in reducing both carbonaceous and nitrogenous material [8], short HRT, less sludge production, high efficient versus shock loading and toxicity [9], and rapid start up. Although the ASFF systems also have unique capability of solid capturing, clogging problem can disrupt pollutant removal efficiency and cause channeling problem [10]. Therefore, regular backwashing to prevent clogging is a key point for the ASFF bioreactor.

High performance of the ASFF systems in treating municipal wastewaters (secondary treatment) with high organic loading rates (OLR) has already been reported [10]. To remove nitrogen from wastewater, treatment plants usually convert the majority of the inlet nitrogen from one form to another using a three step biological process. At the first, organic-nitrogen is converted to ammonia-nitrogen by an anaerobic process (Ammonification). Then, ammonia-nitrogen is converted to nitrate-nitrogen by an aerobic biological process (Nitrification). Finally, nitrate-nitrogen is converted to nitrogen gas biologically in an anoxic environment (Denitrification). Due to the high solids retention time, appropriate condition for the growth and activity of nitrifying bacteria is provided in the ASFF system which can be used for simultaneous carbon removal and nitrification [1]. The ASFF system which has been primarily used to remove carbonaceous material could achieve partial nitrification at ammonium loadings up to

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http://dx.doi.org/10.1016/j.jiec.2015.06.034
1226-086X/

## Nomenclature

| | |
|---|---|
| UP/ASFF | Upflow partially aerated submerged fixed-film |
| COD | Chemical oxygen demand |
| N/A | Ratio between non-aerated to aerated zones |
| OLR | Organic loading rate |
| NLR | Nitrogen loading rate |
| HRT | Hydraulic retention time |
| SS | Suspended solid |
| DO | Dissolved oxygen |
| EUI | Electrical energy use intensity |
| EPC | Energy performance coefficient |

**Table 1**
Composition of both synthetic and real wastewaters used in the experiments.

| Characteristics | Synthetic wastewater | Real wastewater |
|---|---|---|
| **COD** | 200–1200 mg/l | 175–550 mg/l |
| **$NH_4^+$-N** | 20–120 mg/l | 110–180 mg/l |
| **$NiSO_4.7H_2O$** | 0.1 mg/l | Not checked (NC) |
| **$KH_2PO_4$** | 2–12 mg/l | NC |
| **$Na_2HPO4$** | 2–12 mg/l | NC |
| **$MgCl_2$** | 0.5 | NC |
| **Urea** | 10 mg/l | NC |
| **Alkalinity** | 350–600 mg/l | 300–600 |
| **$ZnCl_2$** | 0.5 | NC |
| **pH** | 6.7–6.9 | 5.8–6.8 |
| **$NO_3^-$-N** | 0 | 10–15 mg/l |
| **$NO_2^-$-N** | 0 | Nil |

1 kg $NH_4^+$-N/m$^3$d [9]. A bulk dissolved oxygen (DO) concentration of 4–5 mg/L should also be maintained within the system to prevent the inhibition of nitrification [11]. In the ASFF systems, a small fraction (2–3%) of the ammonium is removed through cell growth and the remaining is eliminated by autotrophic bacteria [6].

Some experiences have been carried out by combining zones of aerobic and anaerobic in series to link nitrification and denitrification for complete nitrogen removal [12]. Importantly, addition of an external carbon source such as methanol and ethanol is also required after the main carbon removal and nitrification [6].

Another alternative is an upflow partially ASFF (UP/ASFF) system with the aerators placed part way up the floating media to form both an aerated and a non-aerated zone inside a single bioreactor [6]. In the system, the lower anoxic zone removes the soluble organic matter and converts organic nitrogen into ammonia, while nitrification happens in the upper aerated zone and removes most of the rest carbonaceous matter [6]. The denitrification efficiency of the UP/ASFF bioreactor depends on the loadings and the recycle ratio to the anoxic area [13].

Aerobic processes such as ASFF systems require high amount of electrical energy for oxygen transfer during carbon removal and ammonia oxidation [9]. In UP/ASFF system, however, energy can be saved due to the denitrification process in addition to the simultaneous removal of carbon and nitrogen.

In this work, the influence of organic and ammonium loading rates as well as aerator location on the performance of carbon and nitrogen removals in a lab-scale UP/ASFF bioreactor was examined for synthetic wastewater. Indeed, the system energy efficiency was evaluated using energy performance coefficient based on the required electrical energy to assess the energy consumption of the system for high nitrogen-content wastewater treatment.

## Materials and methods

### *Wastewater*

Table 1 Synthetic wastewater was prepared by using tape water enriched by sodium acetate ($CH_3COONa$) as a carbon source, ammonium chloride ($NH_4Cl$) as a nitrogen source and potassium dihydrogen phosphate ($KH_2PO_4$) as a phosphorus source with varies COD:N:P ratios. Real municipal wastewater was provided from the wastewater plant of Tabriz city. Table 1 shows specification of the real and synthetic wastewaters used in the present study.

### *Experimental set-up*

Experiments were carried out in a lab-scale set-up, a scheme of which is illustrated in Fig. 1. Plexiglas cylindrical column (11 cm internal diameter, 90 cm height) with a working volume of 7.6 L was used as a bioreactor. The bioreactor was packed with 830 pieces of a special polypropylene support media (18 mm height, 16 mm outer diameter, 15 mm inner diameter). The supporting media had a porosity of 89% and a specific surface area of 320 m$^2$/m$^3$. At the top of the packed media, a perforated plate was installed to make the media submerge inside the bioreactor. The sampling ports were used to take the samples from different depths of the bioreactor. To form both zones of aerated (aerobic) and non-aerated (anoxic) within the bioreactor, air after passing through a filter was introduced part way up the floating media and the aerobic and anoxic zones were connected by a recycle loop (15 mm diameter). Wastewater was introduced at the bottom of the bioreactor to provide an upflow current of liquid. The aeration rate was simply determined using a flow meter (Azmoon Motamam Co.). A peristaltic pump (Roller Pump RP-1000, Eyela) calibrated according to the desired flow rate was also used to adjust the influent liquid. A 100 L reservoir tank was used to supply wastewater to the bioreactor. The bioreactor was operated at room temperatures of 25 ± 3 °C.

### *System start-up and experimental procedure*

At first, the bioreactor was filled with municipal wastewater containing 1.5 L seed sludge provided from the wastewater treatment plant of Tabriz city. In order to form initial biofilm on packing media, the system was operated at ambient temperature for two weeks in batch mode with an aeration of 3 L/min. After inculcation, the bioreactor was fed real wastewater during the first week and then synthetic wastewater from the second week. After the initial formation of biofilm, the bioreactor mode was changed to continuous and the HRT was adjusted to 6 h. The average DO concentration in the upper zone was 4 mg $O_2$/L while the concentration was always below 0.5 mg $O_2$/L in the lower zone. After achievement of steady state condition, experiments were conducted to study the bioreactor performance.

Table 2 Operation period of each run was considered to be 17 days, and OLR and nitrogen loading rate (NLR) values in the first nine runs were changed randomly by increasing or reducing the COD and ammonium values with keeping COD:N:P ratio of 100:10:1 (Table 2). During the last eight runs, the COD concentration was kept constant at around 450 mg/L (1.5 kg COD/m$^3$d) while ammonia concentration was varied from 35 to 100 mg/L (0.12–0.33 kg $NH_4^+$-N/m$^3$d). The HRT values fluctuated in the first nine runs from 2 to 19 h and remained constant at 7.3 h in the rest experiments. Instead, the ratio between non-aerated and aerated zones (N/A) value was kept at 0.5 in the first nine runs and fluctuated between 0.5 and 2 in the remaining runs, as shown in Table 2. The bioreactor was continuously fed based on the experimental strategy and perfor-