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Operating characteristics of baffled reactor under microaerobic conditions

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ABSTRACT

A comparative experimental study was conducted on chemical oxygen demand (COD) elimination, effluent volatile fatty acids (VFAs), biogas production, granular sludge average particle-size distribution, and other indicators of baffled reactors operated under microaerobic or anaerobic conditions. The results show that the addition of an appropriate amount of oxygen improves COD elimination rate, increases biogas production, and reduces the effluent VFA concentration of the anaerobic baffled reactor (ABR), with no toxicity toward the methane bacteria. Regarding influent COD levels in the microaerobic baffled reactor of 1,320 ± 20 mg/L, 1,860 ± 20 mg/L, 2,550 ± 20 mg/L, 3,150 ± 20 mg/L, 3,620 ± 20 mg/L, and 4,150 ± 20 mg/L, compared with those in the ABR, the COD elimination rates increased by 3.45%, 2.27%, 1.98%, 1.82%, 1.84%, and 1.50%, respectively, and biogas production levels increased by 155.76%, 114.93%, 94.90%, 92.16%, 87.38%, and 48.94%, respectively. The effluent VFA concentrations of the two reactors were both less than 150 mg/L, with the effluent VFAs of the microaerobic baffled reactor less volatile and lower in concentration, with steadier change. The granular sludge average particle-size distribution of the microaerobic baffled reactor was mainly concentrated at 1–2 mm, indicating the enhanced activity of the granular sludge.

Keywords: Baffled reactor; Microaerobic; Wastewater; Operating characteristics

1. Introduction

Anaerobic baffled reactors (ABRs) are the new third-generation treatment technology for anaerobic organisms, which are derived from the process design idea of a staged multiphase anaerobic reactor [1,2]. With this technology, several baffles are present vertically in a reactor, dividing it into several cell compartments connected in series. This enables the wastewater to pass through each cell compartment along the baffles, so that all the stages of anaerobic metabolism are separated [2,3]. As each cell compartment easily forms the dominant microbial population that accommodates its treatment phase, the functions of the different microbial populations are performed to the fullest. Numerous studies have proven that ABR technology has various advantages over other anaerobic reactors. These advantages include high treatment efficiency, stable operation, strong anti-shock and load-bearing capacity, low investment, low operating cost, and simple operation and maintenance [2].

The technology of microaerobic water treatment has emerged recently, which means generally that the mass concentration of dissolved oxygen (DO) in the reactor environment is in the range 0.3–1.0 mg/L [4]. Relevant studies show that methane bacteria are viable in the presence of an appropriate amount of oxygen and could show even higher methanogenic activity [5–9]. Many substances that are resistant to degradation can be degraded thoroughly via the involvement of both aerobic and anaerobic bacteria, or, alternatively,

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with a combination of oxidation and reduction [10]. When a small amount of oxygen is added to an anaerobic reactor, the processes of anaerobic and aerobic metabolism occur simultaneously. In the anaerobic reactor, the presence of aerobic bacteria induces the degradation of the intermediates generated via anaerobic metabolism at any time. In addition, the accumulation of toxic intermediate metabolites is reduced, so that operation of the anaerobic reactor is more stable [11] compared with that of a conventional aerobic treatment system. Furthermore, the microaerobic system has higher oxygen utilization, less sludge production, superior dissemination, and higher application value.

In this work, a comparative experimental study was conducted on the operating characteristics of baffled reactors under microaerobic or anaerobic conditions. In addition, the feasibility of the baffled reactor relevant to efficient and stable operation under microaerobic conditions was analyzed. This analysis was conducted in an attempt to provide a theoretical basis for the further application of baffled reactors in efficiently treating industrial wastewater and domestic wastewater with hard-to-degrade, toxic organic substances.

2. Materials and methods

2.1. Experimental apparatus

The baffled reactor was manufactured from polymethyl methacrylate, with dimensions of 550 mm × 250 mm × 400 mm (L ×W × H) and an effective volume of 41.25 L. The reactor is divided into four compartments, each of which comprises an upper and a lower chamber (width ratio is 4:1 for both). A guide plate, with a 45° chamfer at the lower end of the baffle, is connected with the upper chamber to distribute the water. This facilitates water delivery to the center of the upper chamber and enables thorough mixing of the sludge and water. Sampling openings are provided at the ends of each compartment, whereas airway openings are provided at the top part. The water influent velocity is controlled via a peristaltic pump, and a hot water jacket preserves the heat. The framework structure of the reactor is shown in Fig. 1.

Aeration via the blower creates the microaerobic conditions in the baffled reactor. The DO and the oxidation–reduction potential in all the baffled reactor compartments are monitored, facilitating regulation and control of the DO concentration by the flowmeter.

2.2. Experimental water quality

Artificial wastewater was selected as the influent for the baffled reactor, with glucose ($C_6H_{12}O_6$) as the organic carbon source, ammonium bicarbonate (NH_4HCO_3) as the nitrogen source, and potassium hydrogen phosphate ($K_2HPO_4·3H_2O$) as the phosphorus source. In the reactor, chemical oxygen demand (COD):N:P = 200:5:1 was maintained. Various substances, such as $FeSO_4·7H_2O$, $CuSO_4·5H_2O$, $CoCl_2·6H_2O$, $NiSO_4$, $MnSO_4·H_2O$, $MgSO_4·7H_2O$, $(NH_4)_6MoO_{24}·H_2O$, and others were added simultaneously to provide trace elements, such as Fe, Cu, Mn, and Ni, in order to facilitate microbial cell synthesis. To regulate the alkalinity, $NaHCO_3$ was used, and the pH in the reactor was maintained at 6.8–7.2.

2.3. Inoculation sludge

The inoculation sludge for the baffled reactor was sourced from the granular sludge of an upflow anaerobic sludge blanket that was used to treat citric acid wastewater. The amount

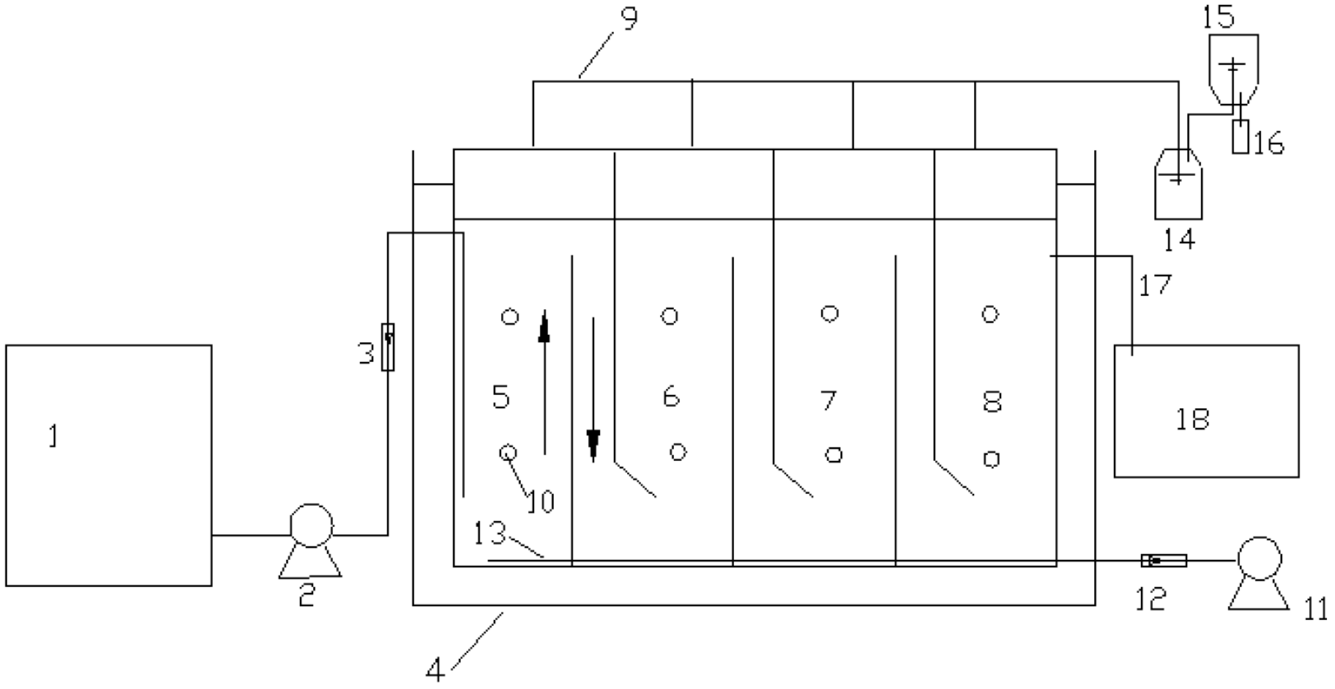

Fig. 1. Experimental configuration (1-water influent tank, 2-peristaltic pump, 3-flowmeter, 4-thermostatic water tank, 5-Compartment I, 6-Compartment II, 7-Compartment III, 8-Compartment IV, 9-gas collector, 10-sampling opening, 11-air blower, 12–flowmeter, 13-aeration tube, 14-watertight bottle, 15-Mariotte bottle, 16-measuring cylinder, 17-water outlet pipe, 18-water effluent tank).

of the inoculation sludge was about 1/3 of the reactor volume. The average sludge concentration of the inoculation sludge in all compartments was 9.15 g/L.

2.4. Experimental method

Two sets of reactors were set up, which were operated in parallel and acclimated after inoculation. The granular sludge was first acclimated in the microaerobic baffled reactor under anaerobic conditions until the influent COD concentration reached 3,000 mg/L and the elimination rate reached 90% higher. Each compartment of the microaerobic baffled reactor was aerated to maintain the concentration of DO at approximately 0.3 mg/L. The oxidation–reduction potential was controlled in the range –380 to –400 mV, after which the low-load microaerobic acclimation phase was initiated. The influent COD concentration was gradually increased until it reached 3,000 mg/L higher, the elimination rate was stable above 90%, and the microaerobic steady operating phase was initiated. After 32 d of inoculating the anaerobic granular sludge in the ABR, the influent COD concentration was 3,188 mg/L, the COD elimination rate reached 91.5%, and the anaerobic steady operating phase was initiated. Subsequently, comparison and analyses were conducted of the COD elimination rate, changes in the effluent volatile fatty acid (VFA) concentration, biogas production, the granular sludge average particle-size distribution, and the physical features of the steady operation. The reactor was operated by gradually increasing the influent COD concentration, with the hydraulic retention time fixed at 24 h.

The operation was divided into six phases, each lasting approximately 60 d. The influent COD concentrations in phases 1–6 were controlled to 1,320 ± 20 mg/L, 1,860 ± 20 mg/L, 2,550 ± 20 mg/L, 3,150 ± 20 mg/L, 3,620 ± 20 mg/L, or 4,150 ± 20 mg/L, respectively.

2.5. Items and methods of analysis

The COD and VFA concentrations were determined by employing standard methods [12]. The DO was determined with a Model 55 analyzer (YSI, USA) [13], whereas the biogas production was determined by using the liquid displacement technique [14]. The granular sludge particle-size distribution was determined via the wet-screening method [15].

3. Results and discussion

3.1. COD elimination

Fig. 2 indicates the total COD elimination rates of the ABR and the microaerobic baffled reactor for the different operating phases. Fig. 3 shows the COD elimination in each compartment of the ABR and the microaerobic baffled reactor. The contribution of each compartment to the overall COD elimination rate is shown in Table 1.

The total COD elimination rate by the ABR gradually increased from Phase 1 to Phase 6, with the average COD elimination rate increasing from 90.42% to 95.36%. In addition, the average COD elimination rate by the microaerobic baffled reactor increased from 93.87% to 96.86%.

With the increase of the influent COD concentration from phases 1 to 6, the average COD elimination rates of Compartment I in the ABR were 75.52%, 73.32%, 71.96%, 70.28%, 68.12%, and 66.91%, respectively, which shows a downward trend. The elimination rate of Compartment II first increased in phases 1 and 2, and then slowly decreased from phases 3 to 6. The elimination rate fluctuated in compartments III and IV, but no significant downward trend was observed. The contribution rates of each compartment of the ABR to the overall COD elimination rate were 76%, 15%, 5%, and 4%, respectively, for compartments I to IV. Microbial adaptation to the environment was extremely strong in Compartment I, thus playing the largest role in the metabolic ability. The degradation of COD was mainly concentrated in Compartment I during phases 1 and 2. From Phase 3 to Phase 6, with the increase in influent concentration, the acids produced in Compartment I to degrade organic substances had an inhibitory effect on the microorganisms in Compartment II, such that the degradation rate of Compartment II was reduced.

The average COD elimination rates for Compartment I in phases 1–6 were 82.06%, 81.73%, 83.78%, 83.35%, 82.50%, and 81.88%, respectively. The COD elimination rate increased and subsequently decreased, whereas it slowly increased in compartments II and IV with the increase in the influent

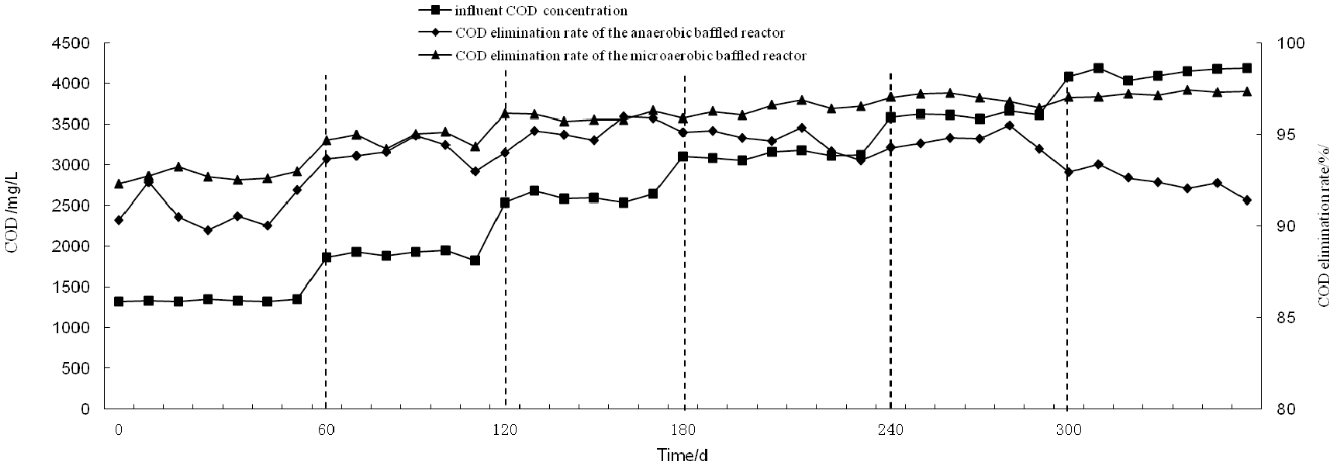

Fig. 2. COD elimination rate of the anaerobic and microaerobic baffled reactors for the different operating phases.

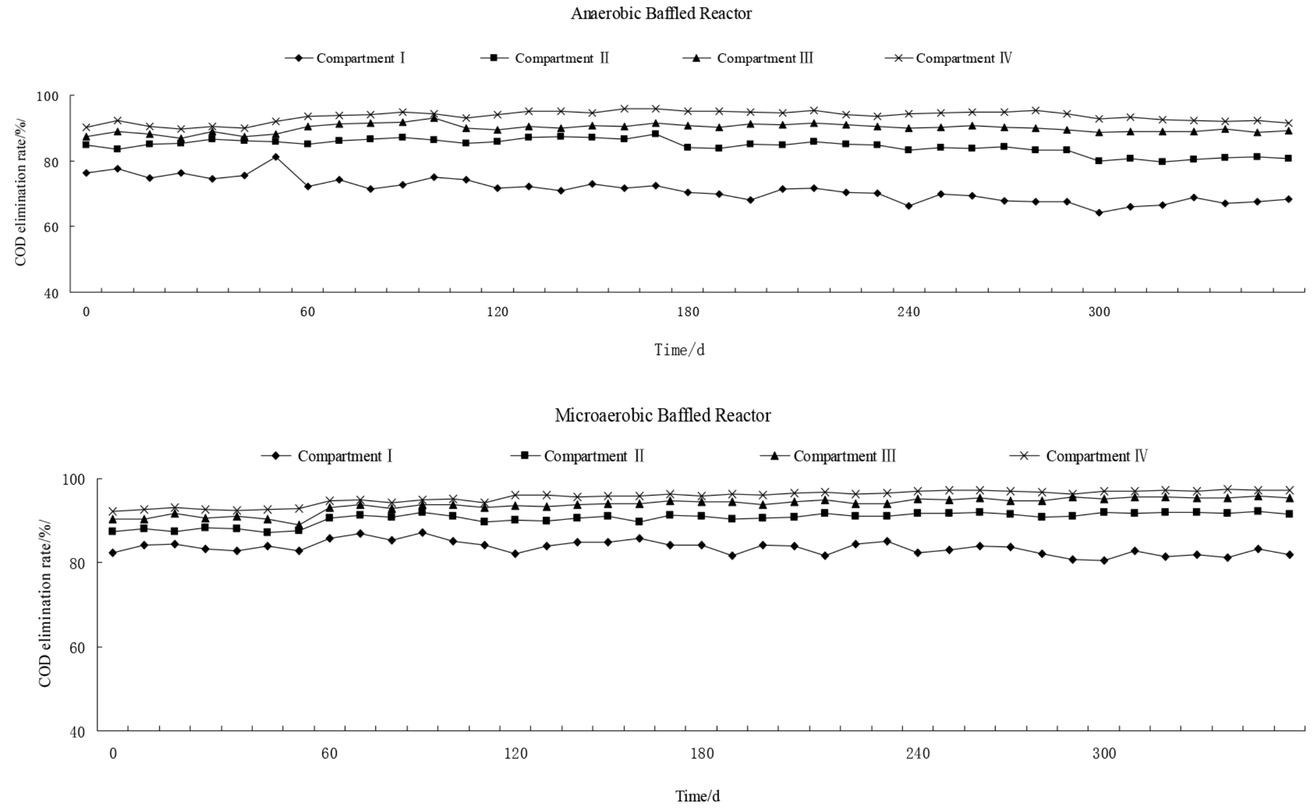

Fig. 3. COD elimination rate for each compartment of the anaerobic and microaerobic baffled reactors for the different operating phases.

Table 1
Contribution of each compartment of the reactors to the overall COD elimination rate

Compartment	I (%)	II (%)	III (%)	IV (%)
Anaerobic baffled reactor	70.01	14.18	4.64	3.8
Microaerobic baffled reactor	82.54	8.01	3.21	2

COD concentration. The contribution rates of compartments I–IV of the microaerobic baffled reactor to the overall COD elimination rate were 86%, 8%, 4%, and 2%, respectively.

Compared with the ABR, the COD elimination rate of the microaerobic baffled reactor was superior, as indicated by the rate of Compartment I being 12% higher than that of the ABR. The total COD elimination rate was almost 2% higher than that of the ABR, indicating that the presence of a small amount of oxygen could improve the COD elimination rate of granular sludge in the reactor.

Many aerobic-anoxia-anaerobic microenvironments in the reactor were formed by adding a small amount of oxygen and exploiting the advantage of a large amount of granular sludge in the baffled reactor. This enhanced the synergistic effect between the aerobic bacteria, facultative bacteria, and anaerobic bacteria in the reactor. The addition of oxygen triggered the aerobic oxidation of the substrate directly, as well as various intermediate metabolites, such as acetic acid, propionic acid, and H_2 [16–18]. Oxygen can act as an electron acceptor in microbial growth and metabolism and a regulator in enzyme reactions. In addition, it can be involved in the electron delivery system and oxidize the reducing power released from anaerobic fermentation. Furthermore, it is involved in the TCA cycle and in biosynthesis and maintains equilibrium of the production and consumption of the system's reducing power. It also facilitates efficient and stable operation [19,20]. In view of these effects, the treatment via the baffled reactor was found superior. The results indicate that the effluent COD concentration was reduced and the COD elimination rate was improved in microaerobic conditions.

3.2. VFA elimination

VFA concentration is considered one of the most important parameters in anaerobic digestion, and the level of VFAs can directly reflect the operating status of a reactor. The changes in the effluent VFA over time in the anaerobic and microaerobic baffled reactors in this study are illustrated in Fig. 4.

The effluent VFA concentrations in the anaerobic and microaerobic baffled reactors were below 150 mg/L, which indicates that the systems operated steadily, with a strong resistance to impact and load. The average VFA and final effluent VFA concentrations of Compartment I in the microaerobic baffled reactor were 496 mg/L and approximately 89 mg/L, respectively. The average VFA and final effluent VFA concentrations of Compartment I in the ABR were 657 mg/L and approximately 109 mg/L, respectively. Compared with the ABR, the effluent VFAs of the microaerobic baffled reactor were less volatile and lower in concentrations, with steadier changes. This can be attributed to the aerobic oxidation of the VFAs, triggered by the addition of a small amount of oxygen in the ABR (microaerobic baffled reactor). This addition decreased the accumulation of VFAs and reduced the effluent VFA concentration in that system.

In addition, Fig. 4 shows that the effluent VFAs in these two reactors significantly increased when the influent COD concentration was increased upon entering the next phase. As the increase in the organic load changed the living environment of the methanogens, the change adversely affected the growth of the methanogens, diminishing their activity. The failing of the on-time degradation of the hydrolytic acidification products [9] resulted in the accumulation of VFAs, which was reflected as a rise in the effluent VFA concentration. The changes in the VFAs of the ABR were more obvious compared with those of the microaerobic baffled reactor, implying that the microaerobic system was more stable and had stronger resistance to impact and load.

3.3. Biogas production

Fig. 5 shows the changes in biogas production for the anaerobic and microaerobic baffled reactors. In phases 1–6 of operation, after an increase in the influent COD concentration, the average biogas production in the microaerobic baffled reactor increased by 155.76%, 114.93%, 94.9%, 92.16%,

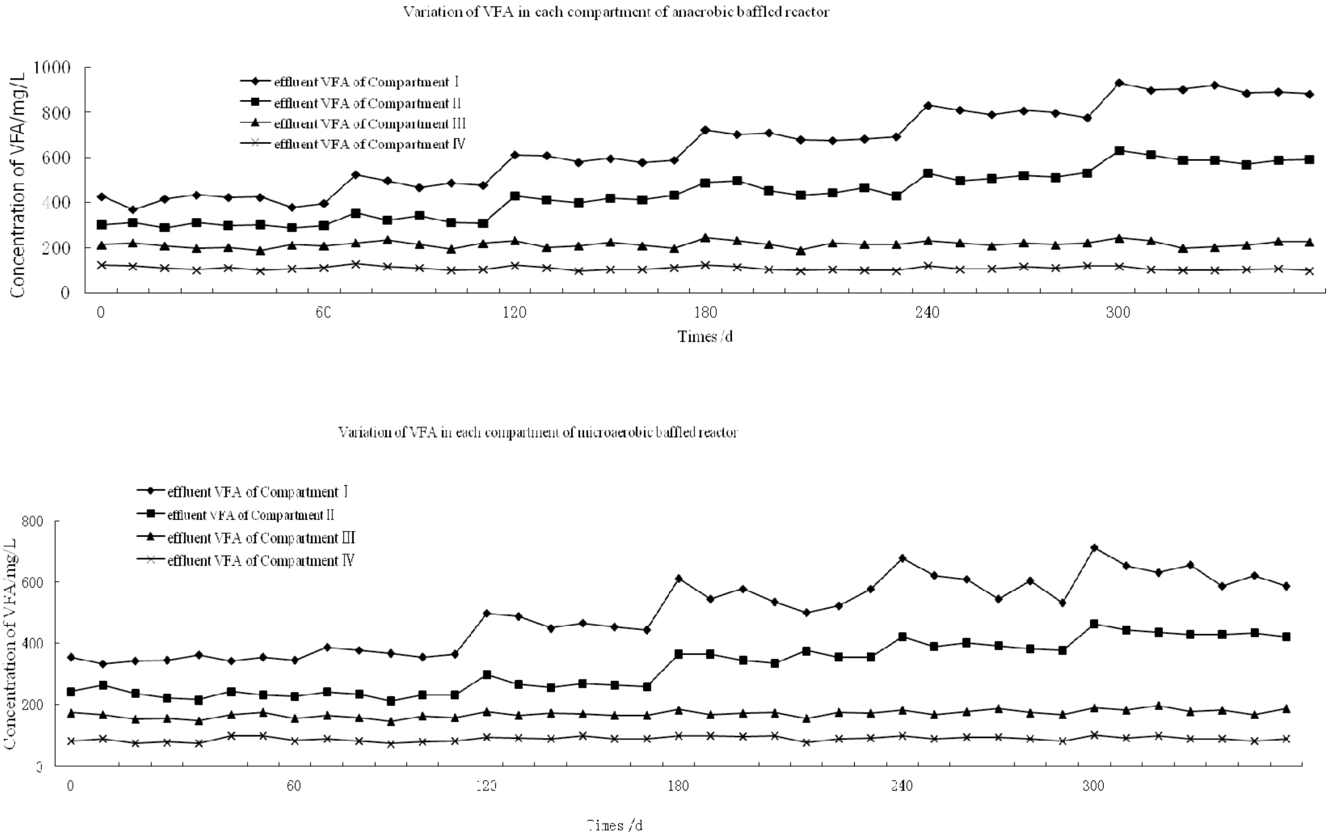

Fig. 4. Changes in effluent VFA concentrations over time in the anaerobic and microaerobic baffled reactors.

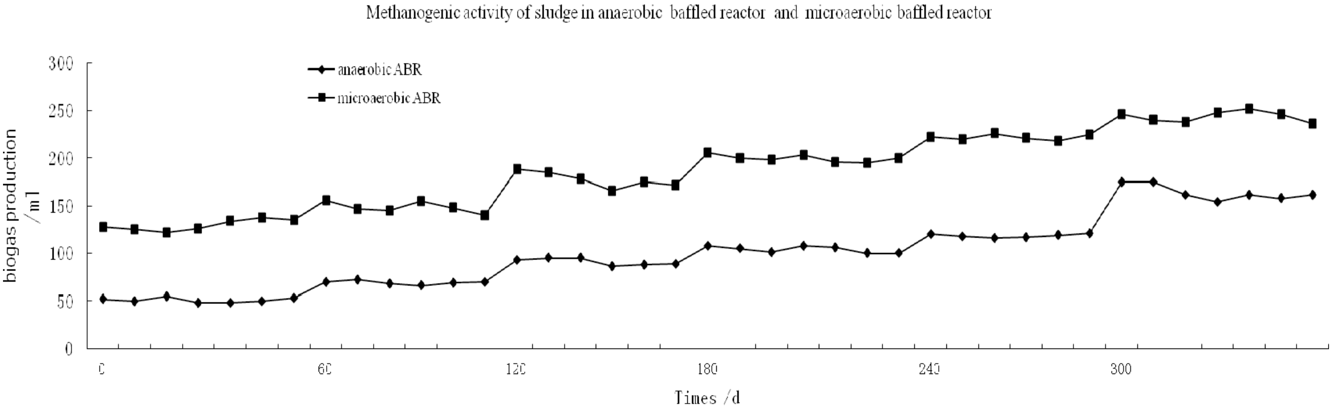

Fig. 5. Changes in biogas production via the anaerobic and microaerobic baffled reactors.

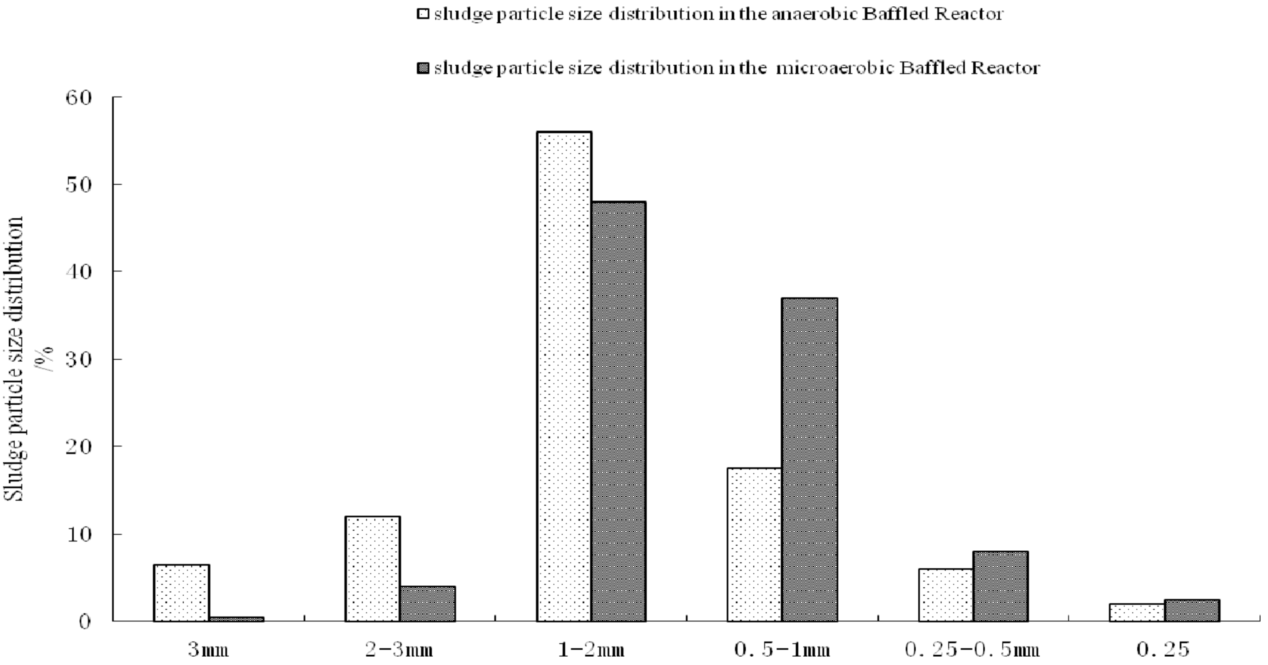

Fig. 6. Changes in granular sludge particle-size distribution in the anaerobic and microaerobic baffled reactors.

87.38%, and 48.94%, respectively, compared with that of the ABR. The biogas production was significantly larger in the microaerobic baffled reactor than in the ABR. This result is a further indication that the addition of a small amount of oxygen does not inhibit, but, in fact, promotes the activity of methanogens.

Regarding the microaerobic baffled reactor, the addition of an appropriate amount of oxygen to the ABR contributed to the growth of aerobic bacteria or facultative bacteria in suspension or on the surface of the granular sludge. The growth of such bacteria consumes oxygen, which keeps the internal environment of the granular sludge in an anaerobic state. In this way, the methane bacteria in the granular sludge were rendered insensitive to the addition of a small amount of oxygen. In microaerobic conditions, oxygen can rapidly oxidize VFAs, H_2S, and other toxic intermediates, In addition, it can reduce SO_4^{2-} selectively to the simple substances of S and $S_2O_3^{2-}$, rather than the toxic intermediate H_2S, thereby alleviating the inhibitory effect on methanogens [9].

3.4. Distribution and morphology of granular sludge particle size

Sludge particle-size distribution is a critical indicator that reflects the degree of sludge granulation [3] and the quality of the granular sludge culture. Fig. 6 illustrates the changes in the granular sludge particle-size distribution in the anaerobic and microaerobic baffled reactors. In the ABR, particle sizes of <0.5 mm, 0.5–1 mm, 1–2 mm, and >2 mm comprised 8%, 17.5%, 56%, and 18.5%, respectively, of the granular sludge, whereas in the microaerobic baffled reactor, they comprised 10.5%, 37%, 48%, and 4.5%, respectively. The particle size of the granular sludge decreased in the microaerobic baffled reactor because of the effect of microaeration. After the microbes had adapted to the microaerobic environment, the particle size of the granular sludge slowly increased, mainly to between 1 and 2 mm, but the relative anaerobic ratio decreased.

The color of the granular sludge in the microaerobic baffled reactor changed from bright black to grey yellow, with some yellow and purple substances in the granular sludge. A layer of slurry floccules on the surface of the granular sludge was observed under an optical microscope.

4. Conclusion

- It is feasible to operate baffled reactors under microaerobic conditions. Compared with the ABR regarding influent COD concentrations of 1,320 ± 20 mg/L, 1,860 ± 20 mg/L, 2,550 ± 20 mg/L, 3,150 ± 20 mg/L, 3,620 ± 20 mg/L, and 4,150 ± 20 mg/L, the COD elimination rates increased by 3.45%, 2.27%, 1.98%, 1.82%, 1.84%, and 1.50%, respectively; the influent VFA concentrations decreased by 22.55%, 27.16%, 14.97%, 12.29%, 19.05%, and 11.50%, respectively; and biogas production increased by 155.76%, 114.93%, 94.90%, 92.16%, 87.38%, and 48.94%, respectively.
- The addition of an appropriate amount of oxygen to the ABR (microaerobic baffled reactor) had no toxic effect on the methanogenic bacteria.
- The average particle size of granular sludge was smaller in the microaerobic baffled reactor than in the ABR, mainly found in the range 1–2 mm.

Acknowledgments

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