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Tolerance to organic loading rate by aerobic granular sludge in a cyclic aerobic granular reactor

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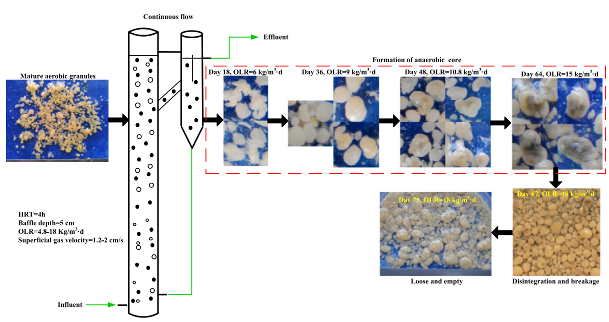
HIGHLIGHTS

- A novel continuous flow aerobic granular reactor was introduced.
- Tolerance to organic load by aerobic granules in the reactor was investigated.
- Evolution of losing stability of AGS was observed.
- Cause of the disintegration of the granules was explored.

GRAPHICAL ABSTRACT



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ABSTRACT

Sodium acetate as carbon source, tolerance to organic loading rate (OLR) by aerobic granular sludge in a cyclic aerobic granular reactor (CAGR) was investigated by gradually increasing the influent COD. AGS could maintain stability in the continuous flow reactor under OLR $\leqslant$ 15 kg/m^3 d in the former 65 days, and SVI, granulation rate, average particle size and water content was 21 ml/g, 98%, 1.8 mm and 97.2% on the 65th day. However, AGS gradually disintegrated after the 66th day when OLR increased to 18 kg/m^3 d, and granules' properties deteriorated rapidly in a short time. High removal rates to pollutants were achieved by CAGR in the former 65 days, but the removal rates of pollutants dropped sharply from the 66th day. With the increase of OLR and particle size, anaerobic cores inside the granules were formed by massive dead cells, while instability of anaerobic core eventually led to the collapse of the system.

1. Introduction

Aerobic granular sludge (AGS) has many incomparable advantages towards activated sludge (Adav et al., 2008; Show et al., 2012), such as: high settling velocity, maintenance of high biomass, simultaneous removal of nitrogen and phosphorus, tolerance to high toxicity, withstand to high organic load, etc. Owing to these advantages, AGS is considered to be one of the most prospective biological wastewater treatment technologies in the 21st century. So far, most of the achievements of AGS are obtained from sequencing batch reactor (SBR) Liu and Tay, 2004; Adav et al., 2008, 2009; Ni and Yu, 2010; Show et al., 2012. Research indicated that aerobic granular SBR (AGSBR) created an ideal environment for aerobic granulation, such as: plug flow along the time and completely mixing in space environment, controllable sludge discharging regulation, continuous and uniform hydraulic shear force, etc. By contrast, the weak hydraulic shear force and nonselective sludge discharging regulation of continuous flow reactor made it difficult for the formation of AGS (Liu and Liu, 2006). And this is why no AGS is found in the traditional activated sludge process which has been operated for more than one hundred years.

Typically, SBR is suitable for small amount wastewater treatment, and it is difficult to connect to continuous operation

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structures. However, continuous flow reactor is widely used in engineering, which has the advantages of flexible, simple to manage, high utilization rate of equipment, etc. Therefore, continuity of aerobic granular sludge reactor has always been the goal of many researchers. To promote the development of AGS technology, some continuous flow aerobic granular reactors (CFAGRs) have been reported in recent years (Juang et al., 2010; Liu et al., 2012; Morales et al., 2012; Jemaat et al., 2013, 2014; Yang et al., 2014). Most of these studies tended to explore the operational parameters to maintain stability of AGS under continuous flow environment, while other studies attempted to realize aerobic granulation in their continuous flow reactors. However, due to unclear of aerobic granulation mechanism, structure of these reactors greatly differed from each other, and their feasibility for maintaining granules' stability under long term operation remained to be inspected. After all, a large number of experimental results obtained from long term operated SBR showed that AGS would be unstable and even disintegrated ultimately (Lee et al., 2010; Show et al., 2012; Wan et al., 2013). Compared with AGSBR, filamentous bulking is much easier to explode in continuous flow reactors (Chudoba, 1985), which greatly endangered the stability of AGS.

Organic loading rate (OLR) is an important operational parameter of bioreactor, which is also an indicator to evaluate the processing capacity of the reactor. As the twin brother of AGS, anaerobic granular sludge reactor is famous for its tolerance to high organic loading rate (Lim and Kim, 2014), for example: EGSB could operate under OLR of 30 kg/m^3 d. By contrast, the highest OLR achieved for aerobic granulation in AGSBR was 22.5 kg/m^3 d (Lopez et al., 2009), while OLR in most AGSBRs was much lower. What's worse, it was found that AGS lost their stability easily under high OLRs (Moy et al., 2002; Zheng et al., 2006; Adav et al., 2010; Li et al., 2010). According to a large amount of achievements obtained from AGSBR, it was shown that OLR had significant influences on granules' macroscopic characteristics and internal bacteria distribution (Moy et al., 2002; Thanh et al., 2009). However, it is quite unclear what the influence of OLR on the stability of AGS in continuous flow reactors. As there are still few successful continuous flow aerobic granular reactors, so it is hard to evaluate what extent of OLR that AGS could withstand in a continuous flow reactor.

According to previous studies (Juang et al., 2010; Liu et al., 2012; Morales et al., 2012; Jemaat et al., 2013, 2014; Yang et al., 2014), medium or low OLRs were usually operated by most CFAGRs, and working volumes of these reactors were usually very small. No report introduced the limitation that AGS could withstand in a CFAGR, and little information indicated that AGS could maintain stability under OLR of 15 kg/m^3 d. On the other hand, it seemed that researchers were keen on to prove AGS could exist in their CFAGRs, but the reason why AGS disintegrated in CFAGRs was usually ignored. Thus, this paper aimed to investigate the stability of AGS under different OLRs (4.8–18 kg/m^3 d). Evolution of losing stability of AGS was observed, while the reason for the disintegration of AGS was also explored. Mature AGS was inoculated in the continuous flow reactor, named cyclic aerobic granular reactor (CAGR), and high OLR was created by gradually increasing COD of the influent until disintegration of the granules. The research was devoted to provide theoretical support for research and development of continuous flow aerobic granular reactor.

2. Methods

2.1. Equipment

Working volume of CAGR was 24.2 L, which consisted of two equal, uniform reactors, namely R_1 and R_2 (Fig. 1). Working volume of the single reactor was 12.1 L, which included the main reaction column (8.4 cm in diameter, 188 cm in height and H/D ratio of 22.4), inclined tube (3.0 cm in diameter and 17 cm in height) and baffle settling tank (7.0 cm in diameter and 37 cm in height). Each single reactor (R_1 and R_2) could realize separation of sludge, gas and liquor. The settling tank was equipped with a removable baffle, while variation of the baffle depth (defined as height of the baffle under effective water level) could create different selection pressure. Fine air bubbles for aeration and mixing were supplied through a dispenser at the bottom of the reactor, while superficial gas velocity was between 1.2 and 2 cm/s.

The system operated in continuous flow with a constant water level. R_1 and R_2 served alternately as the first and the second reactor, while the operational mode was similar to LUCAS process (two reactor type). The system was automatically controlled by a programmable logic controller. Wastewater was filled into the reactor from the bottom inlet through a peristaltic pump (BT100-1 L, Longer). Flow direction of R_1 and R_2 was controlled through ON/OFF of six electromagnetic valves. Cyclic time of the reactor was 4 h, flow direction of the two reactors switched every 2 h. That was: wastewater was firstly pumped into R_1 and finally discharged from R_2 in the former 2 h, then, it firstly flowed into R_2 and finally discharged from R_1 in the following 2 h, which continuously circulated in the following time. Liquid, gas and sludge of mixed liquor in each reactor were separated through the inclined tube and baffle settling tank. Supernatant fluid was discharged from the upper outlet, while mixture of screened sludge and liquor returned back to the main reaction column. Water temperature was controlled between 10 and 20 °C through a constant temperature heater. Other operational parameters could be seen in Table 1.

2.2. Seed sludge

Mature AGS was inoculated for the startup of CAGR. Initial MLSS was controlled to about 5000 mg/L. The AGS was pale yellow and irregular, which had a clear outline. SVI, MLVSS/MLSS, average particle size, granulation rate, the amount of EPS, PN/PS and water content of the AGS were 60 ml/g, 0.8, 1.18 mm, 92.32%, 37.36 mg/g MLVSS, 1.4 and 97.8%.

2.3. Media

The system was continuously fed with simulated wastewater (SW). Composition of SW was presented in Table 2. Concentration of COD, NH_4^+–N and TP were gradually increased according to the growth of microbial, while other components were kept stable.

2.4. Rejection rate

Rejection rate is used to evaluate the selective interception ability of AGS by CAGR, which defined as the percentage of the amount of AGS in reactor after one HRT's operation to the amount of AGS in the reactor when the test started. Rejection rate could be calculated as Eq. (1):

$$\text{Rejection rate} = 1 - \frac{\text{Concentration of granular sludge of the effluent}}{\text{Concentration of granular sludge of the reactor}} \times 100\% \quad (1)$$

2.5. Analysis methods

pH, COD, NH_4^+–N, NO_3^-–N, NO_2^-–N, TP, conductivity, SV, SVI, MLSS, MLVSS and water content were carried out according to standard methods (APHA, 1998). [TIN] = [NH_4^+–N]+[NO_3^-–N]+[NO_2^-–N]. Size