A case for aerobic sludge granulation: from pilot to full scale
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ABSTRACT
A pilot-scale sequencing batch reactor (SBR) treating 120 m³/d of a town’s wastewater was set up in 2009 and aerobic granules with a mean diameter of 0.28 mm, mixed liquor suspended solids (MLSS) of 7,500 mg/L and sludge volume index (SVI) of 43 mL/g were achieved. A full-scale SBR with 50,000 m³/d for treating a town’s wastewater was operated in 2010 and aerobic granules with a mean MLSS of 2,285 mg/L and SVI of 52.5 mL/g were obtained. Aerobic granules had excellent performances of chemical oxygen demand (COD) and NH₄⁺-N removal and remained stable for a long time. Raw wastewater and SBR operating mode had a positive effect on aerobic granule formation. Therefore, aerobic granular technology could be successfully applied in the full-scale bioreactor under specific conditions. Future development of aerobic granular technology is the application in full-scale continuous-flow reactors.

INTRODUCTION
Aerobic granular sludge is a promising biotechnology in wastewater treatment. Since aerobic granules were successfully cultivated in laboratory reactors (Mishima & Nakamura 1991; Morgenroth et al. 1997), the subject has attracted more attention due to its unique properties of a more compact structure, better settling ability, and higher biomass concentration (Show et al. 2012; Khan et al. 2013). Most of the previous basic research on aerobic granular sludge was conducted in laboratory-scale sequencing batch reactors (SBRs) (Liu & Tay 2004; Adav et al. 2008; Lee et al. 2010).

The first pilot-scale reactor of aerobic granules was set up in September 2003 in Ede, The Netherlands. It was composed of two parallel biological reactors with a height of 6 m and diameter of 0.6 m, and fed with real wastewater (de Kreuk 2006). In the following years, the pilot-scale reactors for aerobic granules flourished (Ni et al. 2009; Morales et al. 2013; Rocktaschel et al. 2015). The successful results in laboratory-scale and pilot-scale SBRs of aerobic sludge granulation implied the feasibility and possibility of application in full-scale reactors.

The first full-scale installation for aerobic granular sludge was operated in Gansbaai wastewater treatment plant (WWTP) in Africa (Giesen et al. 2013). It included three reactors with a height of 7 m and diameter of 18 m. It was considered to be a milestone for aerobic granular technology in larger-scale reactors and also confirmed the applicability of the technology in practice. It was also reported that two other full-scale SBRs on aerobic granules were successfully applied in the Netherlands (Giesen et al. 2013) and China (Li et al. 2014a).

This study describes the aerobic granular technology successfully used in pilot-scale and full-scale SBRs in a WWTP in China. The characteristics of granules, reactors’ performances, and the reasons for granulation are discussed. It is hoped that this study can shed new light on promoting the application of aerobic granules in full scale.
METHODS

Wastewater and seed sludge

The pilot-scale and full-scale SBRs were located in a WWTP, where raw wastewater included approximately 50% domestic sewage and 70% industrial wastewater. The average influent biochemical oxygen demand/chemical oxygen demand (BOD/COD) ratio was only about 0.23 which belonged to bio-refractory wastewater. Raw wastewater contained some special chemical elements of Na, Cl, Ca, Mg, Fe, and Si, which accounted for 35.5%, 17.6%, 3.4%, 4.1%, 0.5%, and 0.4%, respectively. The characteristics of raw wastewater in pilot-scale and full-scale SBRs are shown in Table 1. The seed sludge was inoculated from the second sedimentation tank of oxidation ditch process in the WWTP. The initial mixed liquor suspended solids (MLSS), sludge volume index (SVI) in pilot-scale and full-scale SBRs were 3,850 mg/L, 78 mL/g and 2,673 mg/L, 75.5 mL/g, respectively.

Pilot-scale SBR

According to the successful cultivation of aerobic granules in a laboratory-scale SBR with working volume of 5.0 L and a height/diameter (H/D) ratio of 2.5 in 2008, a pilot-scale SBR was set up in 2009. Working volume of the pilot-scale SBR (Figure 1) with two parallel columns was 31.4 m³ (diameter of 2 m, height of 6 m, and H/D of 2.5) and the volumetric exchange ratio was 50%. The pilot-scale SBR system was made up of a grit chamber, a service tank, and two parallel columns (Figure 1(a)). Figure 1(b) shows its flow chart. The cycle time consisted of fill (40 min), aeration (120 min), settling (60 min), and discharge (20 min) stages. After 7 days, the settling time was changed to 20 min. It is worth noting that the Agnail aeration device was employed in the pilot system to control the particle size of aerobic granules. The Agnail aeration device and air pipe layout are shown in Figure 2.

Full-scale SBR

The full-scale SBR system included fine screening and regulating reservoir, pump plant, primary sedimentation tank, hydrolysis tank, SBR, and advanced treatment process, and is shown in Figure 3.

The full-scale SBR (Figure 4) with a treatment capacity of 50,000 m³/d was built and went into operation in 2010. It consisted of four separated tanks with a length of 55 m, width of 38 m, depth of 6 m, and H/D of 0.09. The full-scale SBR had a volumetric exchange ratio of 50–70%. The cycle time consisted of fill (40 min), aeration (240 min), settling (60 min), and discharge (30 min) stages. After 25 days, the settling time was changed to 40 min. The settling time was changed to 50 min after 180 days.

Analytical methods

COD$_{Cr}$, NH$_4$-N, SVI with 30 min settling time (SVI$_{30}$) and MLSS were analyzed in accordance with Standard Methods (APHA 1998). Biological oxygen demand (BOD$_5$) was measured using the WTW OxiTop system. The morphology of sludge was observed by an Olympus CX31 microscope and a digital camera (Canon EOS 30D). The size of granules was analyzed by an image analysis system (image-Pro Plus 6.0, Media Cybernetics).

RESULTS AND DISCUSSION

Aerobic granulation in pilot-scale SBR

Figure 5 shows MLSS and SVI in the pilot-scale system on the first 85 days. The SVI decreased rapidly from 78 to 45 mL/g on day 28, and then remained stable. Simultaneously, MLSS increased promptly from 3,800 to 8,488 mg/L on day 46, then decreased gradually and then remained stable. To improve the sludge properties, measures of improving COD volume loading and shortening the
settling time were taken. Small aerobic granules were visible to the naked eye after 7 days' operation. On day 20, the sludge had almost been conglomerated with loose structure. On day 50, aerobic granular sludge with dense structure and irregular outline was dominant in the reactor (Figure 6). Finally, aerobic granules with average diameter and SVI of 0.28 mm and 43 mL/g were obtained. The granular size (Table 2) was controlled around 0.3 mm by the Agnail aeration device, which prevented granules from growing too large. The granules in the pilot-scale SBR were smaller than the full-scale SBR. This indicated that the Agnail aeration device played an important role in controlling the size of granules in the pilot-scale SBR.

The influent and effluent COD and NH$_4^+$-N in the pilot-scale SBR on the first 85 days are shown in Figure 7. After around 26 days' running, the effluent COD and NH$_4^+$-N decreased to 120 mg/L and 3.2 mg/L, respectively. After 50 days, COD removal rate was maintained at about 88% and NH$_4^+$-N was almost all removed. The system was operated continuously for more than 400 days and maintained high removal efficiencies for pollutants. The result indicated aerobic granules could be formed and maintained in a
pilot-scale SBR with low H/D ratio, and also proved the feasibility of achieving aerobic sludge granulation in a full-scale WWTP reactor.

**Aerobic granulation in full-scale SBR**

The MLSS and SVI in the full-scale SBR on the first 85 days are shown in Figure 8. With operation, the SVI declined to 42.5 mL/g after 15 days. On day 22, the SVI increased to 62 mL/g and then fell to 42 mL/g after 28 days. The average SVI remained around between 40 and 55 mL/g after 85 days. As well, the MLSS gradually increased to 5,512 mg/L on day 25. After 135 days, the MLSS was maintained between 2,800 and 4,000 mg/L due to discharging a certain amount of sludge every day including granules. Finally, excellent aerobic granules with a diameter of 0.5 mm, SVI of 47 mL/g were achieved on day 337. Additionally, Figure 9 shows that aerobic granules could remain steady from day 337 to day 1,425 in full-scale SBR. After complete granulation on day 337, the COD and NH\textsubscript{4}\textsuperscript{-N} removal rate were detected continuously for two months (Figure 10). The effluent COD and NH\textsubscript{4}\textsuperscript{-N} were about 90 mg/L and below 1 mg/L, respectively. The effluent COD and NH\textsubscript{4}\textsuperscript{-N} met the wastewater discharge standard in China (COD < 100 mg/L, NH\textsubscript{4}\textsuperscript{-N} < 25 mg/L). This suggested that the full-scale system with aerobic granular technology could resist organic loading shock and had excellent performances of COD and NH\textsubscript{4}\textsuperscript{-N} removal rates, although the influent quality changed greatly. It was detected that *Flavobacterium* and *Thauera* were significant in full-scale SBR. *Thauera* played an important role in nitrogen removal (Li et al. 2014a).

**Possible reasons for aerobic granulation**

Aerobic granulation was influenced by many operational parameters, such as seed sludge, substrate composition, feeding strategy, settling time, organic loading rate, reactor design, and aeration intensity (Adav et al. 2008). Previous studies have confirmed that multi-valent cations such as Ca\textsuperscript{2+}, Fe\textsuperscript{3+}, Mg\textsuperscript{2+}, Si\textsuperscript{4+} act as a bridge or nuclei to accelerate microbial aggregation (Ren et al. 2008; Konczak et al. 2014; Wan et al. 2015). It has also been reported that a certain
amount of salt benefited performance and increased the compactness of granules (Li & Wang 2008). Many studies have proven that the mentioned conditions play important roles in aerobic sludge granulation (Qin et al. 2004; Liu & Tay 2008; Liu et al. 2011). A feast-famine regime, especially periodic starvation, has been revealed to have a profound effect on cell hydrophobicity, which was a key factor that affected aerobic granulation (Liu & Tay 2008). The settling time was considered to be a major factor controlling granulation (Qin et al. 2004). The common reasons for sludge granulation in pilot-scale and full-scale SBRs were concluded to be the following:

- The raw wastewater contains large amounts of Na, Cl, Mg, Ca, Fe, and Si (Li et al. 2014a), which enhanced aerobic sludge granulation. It is concluded that the composition of the raw wastewater played a profound role in aerobic granulation in WWTPs.
- SBR operating mode with periodic feast-famine, shorter settling time, and no return sludge pump enhanced the granulation of aerobic sludge.

### Future development of aerobic granular technology

Until now, major aerobic granules were cultivated in SBRs although continuous-flow modes have been commonly used in wastewater treatment plants. Future development of aerobic granular technology is the application in continuous-flow process.

This full-scale SBR was ended in October 2014 because improving treatment ability to meet the strict wastewater discharge standard was required in China. The SBR process did not match with the existing units of subsequent coagulation, sedimentation, and filtration, which were continuous-flow for advanced treatment processes. Hence, it was decided to modify the SBR to a continuous-flow process in this plant.

A modified oxidation ditch with an adjustable volume intraclarifier (Li et al. 2014b) and a reverse flow baffled reactor (RFBR) (Li et al. 2015) were proposed for aerobic sludge granulation in a continuous-flow process. Both modified reactors were operated in a continuous-flow mode and achieved success in aerobic sludge granulation for treating real wastewater in this WWTP.

In the modified oxidation ditch, the volume and area of settling area were adjusted by movement of a vertical baffle to control settling time. The RFBR was divided into several cells using baffles; influent started from a right to left direction (forth flow) and then switched from left to right (back flow); settling time was controlled by adjusting the inflow rate and settling cell volume. These showed that periodic feast-famine, shorter settling time, high shear force, and no return sludge pump were designed to enhance the granulation of aerobic sludge. It is predicted that aerobic granules

### Table 2 | The average size of granules in pilot-scale SBR

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<th>Time (d)</th>
<th>Size (μm)</th>
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in continuous-flow reactors will be studied in full scale in this WWTP. Future development of aerobic granular technology is the application in full-scale continuous-flow reactors.

CONCLUSIONS

Excellent aerobic granules were obtained in pilot-scale and full-scale SBRs fed with real wastewater. Additionally, two systems had excellent performances in terms of COD and NH₄⁺-N removal. The raw wastewater and SBR operation mode were responsible for aerobic sludge granulation in pilot-scale and full-scale SBRs. Aerobic granular technology could be feasible to apply in full-scale systems if sufficient conditions were provided.

REFERENCES


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