Control of sludge settleability based on organic load and ammonia nitrogen load under low dissolved oxygen

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ABSTRACT

Controlling dissolved oxygen (DO) at low level can save energy for wastewater treatment plants (WWTPs), but it is easy to induce filamentous sludge bulking. Through establishing the kinetic equation of sludge settleability, ammonia nitrogen (NH$_4^+$-N) load and organic load (food-to-microbe ratio, F/M), the mechanism of the competitive relationship between filamentous and flocular bacteria under low DO was analyzed. The results showed when DO, NH$_4^+$-N load and F/M were in the range of 0.15–0.35 mg/L, 0.035–0.15 d$^{-1}$ and 0.12–0.42 d$^{-1}$, respectively, the mass transfer limitation of organic matter was the main factor determining the dominant growth of filamentous bacteria. When DO, NH$_4^+$-N load and F/M were in the range of 0.35–0.65 mg/L, 0.035–0.065 d$^{-1}$ and 0.12–0.22 d$^{-1}$, respectively, the mass transfer limitation of NH$_4^+$-N was the main factor determining the dominant growth of filamentous bacteria. When DO was low, no matter how NH$_4^+$-N load and F/M changed, the growth of filamentous bacteria was promoted. When DO and F/M were in the range of 0.35–0.65 mg/L and 0.22–0.42 d$^{-1}$, respectively, no matter how NH$_4^+$-N load and F/M changed, the growth of filamentous bacteria was inhibited. Therefore, in actual operation, ensuring relatively low DO and high F/M was beneficial for the sludge settleability improvement.

Key words | limited filamentous bulking, low dissolved oxygen, mass transfer, sludge settleability

INTRODUCTION

The activated sludge process has many advantages such as simple configuration, flexible operation, convenient maintenance, and excellent effluent. Although it has been more than 100 years since its invention, it is still the most popular process in domestic and foreign wastewater treatment plants (WWTPs) (An et al. 2016). In order to ensure the stability of effluent quality, the activated sludge must be maintained in good condition, which is not only to ensure a strong activity, but also to regulate the proportion of microorganisms, especially filamentous and flocular bacteria. Otherwise filamentous sludge bulking will occur (Wang et al. 2017). In severe cases, activated sludge will be lost from the secondary sedimentation tank. So how to control sludge settleability in good condition is very important. There are many factors that affect sludge settleability, such as food-to-microbe ratio (F/M), NH$_4^+$-N load, dissolved oxygen (DO) concentration, temperature, and pH (Cao et al. 2018). Due to the large specific surface area, filamentous bacteria are more competitive at low substrate concentrations (Duan et al. 2016). Li found that when F/M was less than 0.1 d$^{-1}$, filamentous bacteria would grow in large numbers to induce sludge bulking (Li et al. 2012). However, van den Akker has found that when the concentration of organic matter was high, filamentous sludge bulking would also occur (van den Akker et al. 2010). In addition, Li found that when NH$_4^+$-N load was low (<0.065 d$^{-1}$), it was not beneficial for the growth of filamentous bacteria (Li et al. 2014). It is generally believed that when DO is less than 0.4 mg/L, the proliferation of filamentous bacteria is initiated. However, Peng found that when DO was in the range of 0.5–0.7 mg/L, there was a good negative correlation between sludge settleability and F/M (Peng et al. 2010).

From above it can be seen that the research results about filamentous sludge bulking were inconsistent, sometimes even contradictory. The actual WWTP is an integrated system affected by multiple factors. The effects of F/M and NH$_4^+$-N load on sludge settleability are different, and the effect of a certain parameter within a specific range is greater. At present, in order to reduce the energy consumption of WWTPs, DO is usually controlled at low level. However,
there are few reports on how various parameters mutually affect the sludge settleability under low DO condition. In this paper, sludge volume index (SVI) was used as a measure of sludge settleability. Through establishing the dynamic model between specific SVI variation rate, NH$_4^+$-N load and F/M, the influence of various parameters in different ranges on sludge settleability under low DO condition was investigated. The mechanism of mass diffusion was used for analysis, which provided a theoretical reference and technical guidance for the regulation of practical sludge settleability.

MATERIAL AND METHODS

Wastewater quality

Simulated domestic wastewater was used in this experiment. Glucose was used as organic carbon source. Sodium bicarbonate (NaHCO$_3$) was added for alkalinity. Ammonium chloride (NH$_4$Cl) and potassium dihydrogen phosphate (KH$_2$PO$_4$) were used as nitrogen source and phosphorus source, respectively. Magnesium sulfate (MgSO$_4$) and calcium chloride (CaCl$_2$) were used as nutrient solution of mineral elements. Nutrient solution contained the following components (per litre): 1.5 g of FeCl$_3$·6H$_2$O, 0.15 g of H$_3$BO$_3$, 0.03 g of CuSO$_4$·5H$_2$O, 0.18 g of KI, 0.12 g of MnCl$_2$·4H$_2$O, 0.06 g of Na$_2$MoO$_4$·2H$_2$O, 0.12 g of ZnSO$_4$·7H$_2$O, 0.15 g of CoCl$_2$·6H$_2$O and 10 g of EDTA (ethylenediaminetetraacetic acid) (Peng et al. 2012). The simulated domestic wastewater quality and preparation details are shown in Table 1.

Experimental apparatus and method

A laboratory-scale sequencing batch reactor (SBR) was used in this experiment. The SBR was made of polymethyl methacrylate with a working volume of 12 L. The sampling ports were evenly arranged along the reactor vertically. pH, DO and oxidation reduction potential (ORP) detection probes were placed in the reactor to monitor parameters online. The inoculated sludge was taken from the aeration tank of a WWTP in Zhengzhou (Henan Province, China). Each SBR cycle consisted of 8 hours which was consisted of instantaneous feeding, aerobic aeration, anoxic stir, sedimentation, drainage and idleness (Zhang et al. 2013). After the anoxic stir, an amount of mixed liquor was discharged to control sludge age (sludge retention time, SRT). According to water-filling ratios, this experiment was divided into five stages, as shown in Table 2.

Establishment of settlement model

The proportion of filamentous and floccular bacteria constantly changed with the operation of the reactor, and so was sludge settleability. By referring to the Monod equation (Luo et al. 2013; Qi et al. 2013) (Equation (1)), replacing the specific growth rate of microorganisms, NH$_4^+$-N

| Table 1 | The quality and the preparation details of the simulate domestic wastewater |
| Wastewater quality parameters | COD (mg/L) | NH$_4^+$-N (mg/L) | PO$_4^{3-}$-P (mg/L) | Alkalinity (CaCO$_3$) | – |
| Concentration (mg/L) | 200–400 | 40–80 | 3.0–6.8 | 200–450 |
| Pharmacy | glucose | NH$_4$Cl | KH$_2$PO$_4$ | MgSO$_4$ | CaCl$_2$ | NaHCO$_3$ |
| Dosage (g/L) | 0.2–0.4 | 0.15–0.3 | 0.02–0.045 | 0.08 | 0.04 | 0.3–0.6 |

| Table 2 | The reactor operation and parameter control |
| Reaction stage | Aerobic aeration (h) | Anoxic stir (h) | Sedimentation (h) | Drainage (h) | Idleness (h) | Water filling ratio | HRT (h) | SRT (d) | NH$_4^+$-N load (d$^{-1}$) | F/M (d$^{-1}$) | DO mg/L | Cycle number |
| I | 4.5 | 1.5 | 0.5 | 0.5 | 1.0 | 0.25 | 32 | 10–20 | 0.026–0.090 | 0.08–0.26 | 0.15–0.65 | 1–45 |
| II | 4.5 | 1.5 | 0.5 | 0.5 | 1.0 | 0.33 | 24.24 | 10–20 | 0.058–0.098 | 0.18–0.39 | 0.15–0.65 | 46–90 |
| III | 5.0 | 1.0 | 0.5 | 0.5 | 1.0 | 0.42 | 19.04 | 10–20 | 0.041–0.087 | 0.13–0.26 | 0.15–0.65 | 91–135 |
| IV | 5.0 | 1.0 | 0.5 | 0.5 | 1.0 | 0.67 | 11.94 | 10–20 | 0.035–0.077 | 0.12–0.33 | 0.15–0.65 | 136–180 |
| V | 4.5 | 1.5 | 0.5 | 0.5 | 1.0 | 0.33 | 24.24 | 10–20 | 0.031–0.090 | 0.14–0.29 | 0.15–0.65 | 181–210 |

HRT: hydraulic retention time.
concentration and chemical oxygen demand (COD) concentration with specific SVI variation rate, NH₄⁺-N load and F/M, respectively. Equation (1) was simplified to Equation (2). F/M and NH₄⁺-N load were divided into several ranges of combinations (shown in Table 3); in each combination the effect of NH₄⁺-N load and F/M on sludge settleability was investigated through mathematical operations, and Equation (2) can be converted to Equation (3). Based on experimental data, the kinetic parameters in each combination can be calculated by linear fitting.

\[
\mu = \mu_{\text{max}} \frac{S_N}{K_s + S_N} - \frac{S_C}{K_s + S_C} \quad (1)
\]

where \( \mu \) = specific growth rate of microorganisms, d⁻¹; \( \mu_{\text{max}} \) = maximum specific growth rate of microorganisms, d⁻¹; \( K_s \) = saturation constant, i.e. substrate concentration when \( \mu = \frac{1}{2} \mu_{\text{max}} \), called half-rate constant, mass/volume; \( S_N \) = influent NH₄⁺-N concentration, mg/L; \( S_C \) = influent COD concentration, mg/L.

\[
\mu = \mu_{\text{max}} \frac{N}{K + N} \quad \text{or} \quad \mu = \mu_{\text{max}} \frac{C}{K + C} \quad (2)
\]

\[
\mu = \mu_{\text{max}} - \frac{\mu}{N} K \quad \text{or} \quad \mu = \mu_{\text{max}} \frac{\mu}{C} K \quad (3)
\]

where \( \mu \) = specific SVI variation rate; \( N \) = NH₄⁺-N load, d⁻¹; \( C \) = F/M, d⁻¹; \( K \) = saturation constant, NH₄⁺-N or F/M load when \( \mu = \frac{1}{2} \mu_{\text{max}}, \) d⁻¹.

**Test analysis project**

COD, suspended solids, mixed liquor suspended solids, SVI, settling velocity, NH₄⁺-N, nitrate nitrogen (NO₃⁻-N), and nitrite nitrogen (NO₂⁻-N) were measured by standard analysis methods (China National Environmental Protection Agency 1997). DO, pH, ORP and temperature were monitored online by using a bench-top DO meter. The microbiological morphology was observed by microscopy (Flex-Axiom, Nanosurf).

**RESULTS AND DISCUSSION**

**Analysis of test results**

F/M, NH₄⁺-N load, and DO were controlled within the ranges of 0.12–0.42 d⁻¹, 0.035–0.15 d⁻¹ and 0.15–0.65 mg/L, respectively. The corresponding SVI fluctuated at 120–220 mL/g. In actual projects, it was found that when filamentous sludge bulking caused by low DO was properly controlled, it will not only save aeration energy, but also improve effluent quality. This condition was called limited filamentous bulking (Guo et al. 2012), in which the proportion of filamentous and floccular bacteria was moderate. In this experiment, activated sludge was in the state of limited filamentous bulking. The variation of SVI under different F/M, NH₄⁺-N load, and DO is shown in Figure 1.

It can be seen that SVI increased from 170 mL/g to 220 mL/g gradually at the first stage, and it showed positive correlation with NH₄⁺-N load (correlation coefficient \( R^2 = 0.952 \)) and F/M \( (R^2 = 0.927) \). At the second stage, when NH₄⁺-N load was unchanged, the positive correlation between SVI and F/M was not obvious \( (R^2 = 0.626) \). At the third stage, SVI decreased from 170 mL/g to 120 mL/g gradually, and \( R^2 \) between SVI and NH₄⁺-N load and between SVI and F/M was 0.775 and 0.905, respectively. At the fourth stage, when NH₄⁺-N load was unchanged, SVI showed a negative correlation with F/M \( (R^2 = -0.961) \). At the initial phase of the fifth stage, when the change of F/M was not obvious, SVI was negatively correlated with NH₄⁺-N load \( (R^2 = -0.990) \). However, at the end of the
fifth stage when NH$_4^+$-N load was unchanged, SVI had no significant correlation with F/M.

In summary, F/M and NH$_4^+$-N load have different effects on sludge settleability. When they changed in the same direction, SVI also showed the same direction of change. When NH$_4^+$-N load was stable and F/M changed, the variation direction of SVI was difficult to determine. When F/M was stable and NH$_4^+$-N load changed, SVI showed negative correlation with NH$_4^+$-N load.

**Establishment of microbial proliferation kinetic model**

According to the method proposed in the section ‘Establishment of settlement model’, the dynamic equation between specific SVI variation rate and NH$_4^+$-N load (F/M) was established. The corresponding kinetic parameters were calculated based on experimental data, as shown in Table 3.

From Table 3, it can be seen that when DO was in the range of 0.15–0.35 mg/L, the $\mu_{\text{max}}$ showed positive value. This meant that no matter how NH$_4^+$-N load and F/M changed, the growth of filamentous bacteria was promoted. According to Equation (3), $K_{\text{F/M}}$ showed negative values; so no matter how NH$_4^+$-N load changed, increasing F/M helped inhibit the growth of filamentous bacteria. That is the reason why many cyclic activated sludge systems (CASS) set a selection zone near influent area: a higher F/M condition was created to inhibit filamentous bacteria. The F/M in an actual CASS selection zone was generally controlled at 0.18–0.25 d$^{-1}$ (Li et al. 2011).

When DO and F/M were in the range of 0.35–0.65 mg/L and 0.12–0.22 d$^{-1}$, respectively, the $\mu_{\text{max}}$ showed positive value under low NH$_4^+$-N load and negative value under high NH$_4^+$-N load, indicating that low NH$_4^+$-N load was beneficial to the growth of filamentous bacteria. The reason was filamentous bacteria had bigger specific surface area, and under low F/M and NH$_4^+$-N load condition they were more likely to obtain the limited nutrient substances (Burger et al. 2017).

However, when F/M was in the range of 0.22–0.42 d$^{-1}$, the $\mu_{\text{max}}$ was negative, indicating that no matter how NH$_4^+$-N load and F/M changed, the growth of filamentous bacteria was inhibited. The $K_{\text{NH}_4^+-\text{N}}$ was positive, which meant increasing NH$_4^+$-N load could promote the growth of filamentous bacteria to a certain extent under this condition.

**Analysis of sludge bulking mechanism**

Theoretically, filamentous bacteria are the skeleton of activated sludge, and floccular bacteria are attached to its surface. When the proportion between the two kinds of bacteria is moderate, activated sludge flocs are compact, and sludge settleability is good (shown in Figure 2(a) and 2(b)). However, when the filamentous bacteria are dominant (shown in Figure 2(c)), sludge settleability would deteriorate. At present, there are some theories such as adsorption selection, kinetic selection, and diffusion selection to explain the competition relationship between filamentous and floccular bacteria (Cui & Zhong 2004; Hou et al. 2012). The excessive proliferation of filamentous bacteria is explained from various angles, and the core is the morphology of filamentous bacteria.
bacteria. That is, filamentous bacteria have large specific surface area and one-dimensional growth direction, whereas the specific surface area of flocular bacteria is relatively small and their growth direction is multidimensional. Low F/M means little organic concentration and long reaction time. Under low F/M condition, organic matter is difficult to diffuse into the interior of flocs. This stimulates one-dimensional growth of filamentous bacteria, so sludge settleability will be deteriorated. Identically, low NH₄⁺-N load means that the nitrogen is limited. Compared with flocular bacteria, filamentous bacteria can easily obtain nitrogen because of their bigger specific surface area. It is considered that the mass transfer efficiencies of NH₄⁺-N and organic matter in various concentration ranges are different. Fick proposed that the diffusion flux is proportional to the concentration gradient; that is, the greater the concentration gradient, the greater the diffusion flux, and the diffusion coefficients can be used to characterize the difference in the effects of F/M and NH₄⁺-N load on sludge settleability in various ranges.

According to kinetic data in the ‘Establishment of microbial proliferation kinetic model’ section, when DO, NH₄⁺-N load and F/M were in the range of 0.15–0.35 mg/L, 0.035–0.15 d⁻¹ and 0.12–0.42 d⁻¹, the mass transfer limitation of organic matter was the main factor determining the dominant growth of filamentous bacteria. With the increase of F/M, organic matter transfer rate was increased; thus the one-dimensional growth of filamentous bacteria was effectively inhibited.

When DO, NH₄⁺-N load and F/M were in the range of 0.35–0.65 mg/L, 0.035–0.065 d⁻¹ and 0.12–0.22 d⁻¹, the mass transfer limitation of NH₄⁺-N was the main factor determining the dominant growth of filamentous bacteria. With the increase of NH₄⁺-N load, the rate of NH₄⁺-N transfer was increased, and the one-dimensional growth of filamentous bacteria was inhibited. When F/M was in the range of 0.22–0.42 d⁻¹, no matter how NH₄⁺-N load changed, the growth of filamentous bacteria was inhibited, indicating that mass transfer was no longer a limiting factor at high concentration condition.

**CONCLUSIONS**

(1) The influence of F/M and NH₄⁺-N load on sludge settleability is different. When they changed in the same direction, sludge settleability showed the same change. When F/M was stable and NH₄⁺-N load changed, sludge settleability was negatively correlated with NH₄⁺-N load. When NH₄⁺-N load was stable and F/M changed, sludge settleability was difficult to predict.

(2) When DO was in the range of 0.15–0.35 mg/L, no matter how NH₄⁺-N load and F/M changed, the growth of filamentous bacteria was promoted. When DO and F/M were in the range of 0.35–0.65 mg/L and 0.22–0.42 d⁻¹, no matter how NH₄⁺-N load and F/M changed, the growth of filamentous bacteria was inhibited.

(3) By analyzing the kinetic equation of specific SVI variation rate, it was found that when DO, NH₄⁺-N load and F/M were in the range of 0.15–0.35 mg/L, 0.035–0.15 d⁻¹ and 0.12–0.42 d⁻¹, the mass transfer limitation of organic matter was the main factor determining the dominant growth of filamentous bacteria. When DO, NH₄⁺-N load and F/M were in the range of 0.35–0.65 mg/L, 0.035–0.065 d⁻¹ and 0.12–0.22 d⁻¹, the mass transfer limitation of NH₄⁺-N was the main factor determining the dominant growth of filamentous bacteria.

**ACKNOWLEDGEMENTS**

This research was supported by a university key scientific research project (17A560029) and the National Major Science and Technology Project for Water Pollution Control and Treatment (No. 2015ZX07204-002).

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