

# Non-filamentous sludge bulking caused by a deficiency of nitrogen in industrial wastewater treatment

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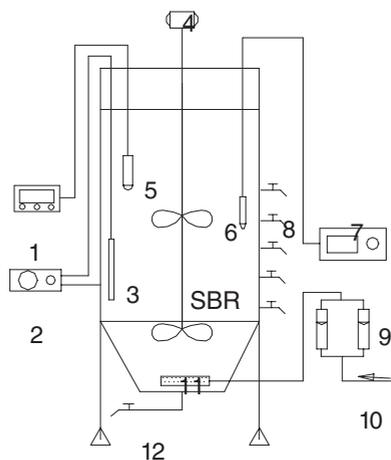
**Abstract** Deficiency in the nutrient supply such as nitrogen usually results in activated sludge bulking and this phenomenon often takes place in the industrial wastewater treatment plants with activated sludge process. The effects of nitrogen deficiency on activated sludge bulking were studied specially in some experiments carried out in a sequencing batch reactor fed with brewing process wastewater in this paper. The experimental results showed that the sludge settled properly at an influent BOD/N value of 100/4. When the value of BOD/N was 100/3, filaments had an excessive growth at one time during the reaction process. Afterwards, the number of filamentous bacteria began to reduce and simultaneously an excessive growth of viscous *Zoogloea* with high percentage of moisture was observed and non-filamentous activated sludge bulking occurred. When the influent BOD/N value was 100/2, the excessive growth of filamentous microorganisms could not be observed at all times and the sludge characterization was similar to the case in which BOD/N value was 100/3. When the value of influent BOD/N was 100/0.94, more serious non-filamentous bulking occurred. Furthermore, the effects of nitrogen deficiency on the nitrogen sources and phosphorus sources utilization rate and the COD removal rate were investigated in the experiments.

**Keywords** Activated sludge; nitrogen deficiency; non-filamentous bulking

## Introduction

In the wastewater treatment plant, a large proportion of activated sludge process problems involve poor solids separation in the secondary settling tank. Bulking is one of the most common and widespread sludge separation problems. It is described by a high sludge volume index ( $SVI \geq 150 \text{ mL/g}$ ) (Novák *et al.*, 1993). Sludge bulking can be divided into the filamentous bulking and the non-filamentous bulking according to the microorganism's condition in the aeration basin. About 95% of sludge bulking is correlated with the excessive proliferation of filamentous bacteria. Generally, the non-filamentous bulking is viscous bulking that can be linked to the extracellular polymers with plentiful hydration water. It is considered the result of abundant Zoogloea microorganisms (Horan *et al.*, 1986). In spite of the fact that this type of Zoogloea microorganisms forms the major part of well settling sludge flocs, in their excessive growth they can produce a severe deterioration of plant effluent characteristics. In a treatment plant it can lead to the production of dilute return and waste-activated sludge streams, hydraulic overloading of solids handling processes, high effluent suspended solids (SS) and biochemical oxygen demand (BOD) as a result of sludge blanket overflow from the secondary clarifier, and in severe cases, washout of the activated sludge culture (Novák *et al.*, 1994).

Because the non-filamentous bulking has occurred unusually, the related references to the prevention and control of any non-filamentous bulking were rare. The nutrient (nitrogen and phosphorus) deficiency was an important factor causing sludge bulking. However, so far, a uniform opinion had not been generated concerning the effect of nutrient deficiency on sludge bulking. And, previously the specialized research concerning this question was rare, and some investigations were just analysis aiming at the operation



1. ORP detector; 2. temperature controller; 3. temperature sensor; 4. electromotion stirrer; 5. ORP sensor; 6. DO sensor; 7. DO detector; 8. sampling; 9. rotor flow meter; 10. compressed air; 11. micropore aerator; 12. blow-down pipe

**Figure 1** Experimental equipment of SBR process

results of the wastewater treatment plants and lacked the technical experimental research. The specialized researches about effects of nitrogen deficiency on sludge bulking were carried out in this paper using brewing process wastewater with sufficient phosphorus source.

### Methods and materials

A schematic diagram, including the on-line examining device and a control system of bench-scale sequencing batch reactor (SBR) process, is presented in Figure 1. The effective volume of reactor was 14 L. In the experiment, brewing process wastewater, which contained many organic components such as various glucides, yeast, alcohol, amino acids and protein, and belonged to easily soluble wastewater with high glucide content, was used as raw wastewater. Influent COD concentration was 600 mg/L, mix liquid suspended solid (MLSS) concentration was maintained at 2,000 mg/L approximately. DO concentration of mixed liquid inside the reactor was about 2 mg/L; and water temperature was approximate 20°. The organic loading was maintained at about 4 kg/(kg·d). In the experiments, influent total phosphor (TP) content was sufficient. Influent total nitrogen (TN) content was changed by adding various amounts of ammonium chloride, and influent BOD/N were 100/5, 100/4, 100/3, 100/2 and 100/0.94 respectively. In the experiments, SVI was used to indicate the sludge settling property and sludge bulking degree. At each influent BOD/N value, many reaction cycles were operated till sludge bulking occurred. Then, the sludge bulking was controlled. After operating the order for several cycles, the reaction began at the next influent BOD/N value. The observation of the microorganisms growth was done under Gram's staining. SVI was carried out in order to evaluate the sludge settling properties. The other items in the experiment contained COD, BOD, DO, MLSS, TN and TP, etc.

### Results and discussions

#### Effects of nitrogen deficiency on sludge settling properties

In the paper, two definitions were introduced firstly. One was maximum of SVI ( $SVI_{max}$ ) and the other was increase rate of SVI ( $V_{SVI}$ ). Under the condition that other environmental factors (such as DO, pH, temperature, etc.) were not changed, SVI could reach a stable value at a certain influent BOD/N value. The stable value was the so-called  $SVI_{max}$ . It

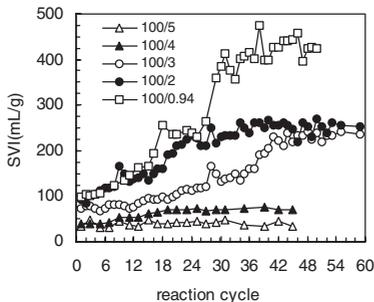
indicated the maximum that SVI could increase at a certain BOD/N value, namely the degree of sludge bulking.  $V_{SVI}$  was an average increasing amount of SVI at each reaction cycle during the period from the first cycle to the cycle in which SVI achieved  $SVI_{max}$  at a certain influent BOD/N along with nitrogen deficiency. It reflected the speed of sludge bulking.

Effects of different influent BOD/N value on sludge settling properties are shown in Figure 2,  $SVI_{max}$  and  $V_{SVI}$  at each influent BOD/N value are presented in Figure 3. Under the condition that nutrient was sufficient (BOD/N value was 100/5), sludge settled well after long term stable operation. SVI value was approximate 40 mL/g. Here the microorganisms in the sludge were floc-forming bacteria primarily, and filamentous bacteria were few.

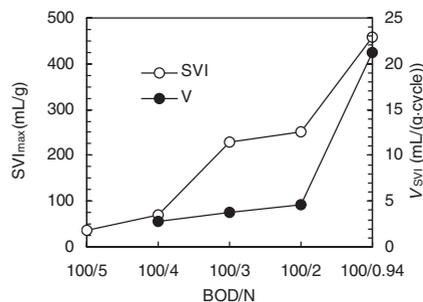
When the influent BOD/N value was 100/4, the SVI increased slightly. After 10 cycles, it increased from 40 mL/g to 70 mL/g and then maintained this value (namely  $SVI_{max}$ ). The  $V_{SVI}$  was 2.81 mL/(g·cycle). Here the microorganisms in the sludge were mainly floc-forming bacteria. The amount of filamentous bacteria was increased a little, but the phenomenon of excessive growth was not observed. The amounts of floc-forming bacteria and filamentous bacteria kept a suitable proportion and settling flocculating properties were good.

The traditional viewpoint considered that only when the nitrogen content in the influent was higher than the value for BOD/N of 100/5, could microorganisms in the activated sludge grow on the rails. But in these experiments, sludge settled well under the condition that influent BOD/N value was 100/4. Here *Zoogloea* had a good state, its configuration was compact, and the sludge bulking phenomenon caused by the excessive growth of filamentous bacteria was not observed. It indicated that in the operation of the SBR process fed with brewing process wastewater, the condition that influent BOD/N value was 100/4 did not form a nitrogen restriction for microorganisms. Therefore, in the operation and management of industrial wastewater treatment in the activated sludge process, in order to decrease treatment cost and avoid eutrophication of the reception water body caused by superfluous industrial nutrient discharge, the nutrient requirements of microorganisms should be evaluated according to wastewater quality. In the nitrogen deficiency wastewater treatment, one need not keep the influent BOD/N value at 100/5, maintaining it at 100/4 could assure the steady operation of the treatment process.

When the influent BOD/N value changed from 100/5 to 100/3 suddenly, SVI increased to 228 mL/g (its  $SVI_{max}$ ) after more than 50 cycles and sludge bulking occurred. There was a variety in the population of microorganisms in the activated sludge during the continuous increase of SVI value. And the variety could be divided into two stages. At the first stage, during the course that SVI increased from the beginning to 160 mL/g, filamentous bacteria augmented gradually and became the dominant bacteria in the activated sludge.



**Figure 2** Effects of BOD/N values on sludge setting



**Figure 3**  $SVI_{max}$  and  $V_{SVI}$  at different BOD/N values

Filamentous bacteria grew quickly and their mycelia stretched out of the boundary of *Zoogloea*. The bridging effect between the mycelia of filamentous bacteria interfered with the agglomeration and compaction of sludge floc so that the settling properties of sludge were deteriorated and SVI increased. But at this stage the degree of sludge bulking was not serious. At the second stage, SVI increased from 160 mL/g to 228 mL/g along with the reaction. In this process, the amount of filamentous bacteria reduced gradually. At the same time, viscous *Zoogloea* with a high percentage of moisture appeared and grew rapidly. When SVI value increased to approximately 228 mL/g, filamentous bacteria could not be observed on microscope examination. Because of the higher influent BOD/N value, excessive carbon sources could not be utilized fully by microorganisms and translated into polysaccharide extracellular storage. The polymer was a highly hydrophilic compound and formed the viscous substance. Lots of viscous substance that was excreted by floc-forming bacteria made the sludge configuration symmetrical and conglutinate, which disturbed the subsiding and compressing of the sludge floc. Sludge settling properties were worsened badly and non-filamentous sludge bulking occurred. Here because of flocculation and sorption of *Zoogloea*, effluent suspended solid concentration decreased and supernatant was limpid.

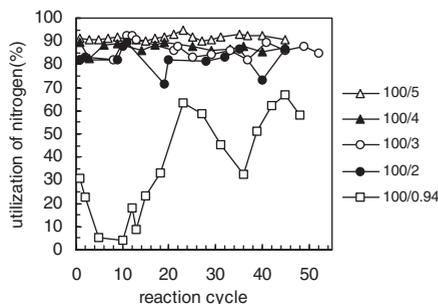
When influent BOD/N changed from 100/5 to 100/2 suddenly, SVI increased from 90 mL/g to 250 mL/g ( $SVI_{max}$ ) and non-filamentous sludge bulking was observed. However, this kind of bulking differed from that happening under the condition that BOD/N was 100/3 in the microorganism population. During the increase of SVI value, floc-forming bacteria were always the dominant bacteria of the sludge microorganisms and the phenomenon that filamentous bacteria proliferated excessively did not appear. Effluent suspended solid was less and supernatant was less lucid.

Under the awful nitrogen deficiency condition that influent BOD/N was 100/0.94, SVI increased rapidly from 90 mL/g to 458 mL/g only after thirty cycles. In this process, excessive growth of filamentous bacteria was not observed all the time and non-filamentous sludge bulking occurred. But the structure of *Zoogloea* was different from that of the forenamed two kinds of cases because the degree of nitrogen restriction was very serious. On the one hand, the percentage of moisture of extracellular polymers that were secreted by floc-forming bacteria and were the main composition of viscous substance increased remarkably. On the other hand, the structure of activated sludge floc was more relaxed and the specific gravity of sludge floc approached that of water because of the presence of viscous substance with a high percentage of moisture. So the settling rate of sludge floc was considerably slow and settling properties deteriorated seriously. This did not appear when the influent BOD/N value was 100/3 and 100/2 respectively. Moreover, under the condition that influent BOD/N was 100/0.94, filtration rate of supernatant was fairly slow. Under the condition that influent BOD/N was 100/0.94, the  $SVI_{max}$  increased obviously compared with that of the two cases mentioned above and  $v_{SVI}$  had a considerable enhancement too.

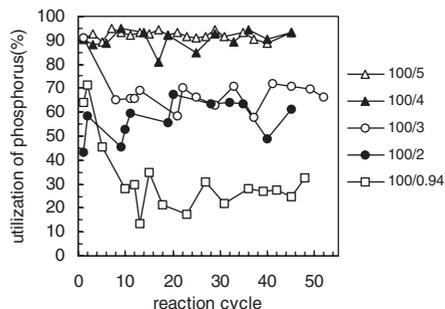
The results in Figure 2 and Figure 3 had shown that, the higher the influent BOD/N value, the more serious the nitrogen deficiency was, the more easily the activated sludge bulking occurred, the more severe the degree of sludge bulking was and the more rapidly sludge bulking occurred.

#### **Effects of nitrogen deficiency on the utilization rate of nitrogen and phosphorus and the degradation of organic matter**

In the activated sludge process the utilization rate of nitrogen and phosphorus was related to the degradation of organic matter. The higher the concentration of organic matter, the more the nutrient requirement for degrading organic matter. If nitrogen and phosphorus content could not meet the requirements of the microorganisms, organic matter degradation and



**Figure 4** Utilization rate of TN at different influent BOD/N value



**Figure 5** Utilization rate of TP at different influent BOD/N value

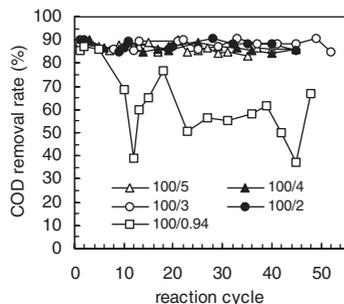
utilization of nitrogen and phosphorus would vary. In the experiments, utilization rates of nitrogen and phosphorus at different influent BOD/N values are shown in Figure 4 and Figure 5 respectively.

It could be seen from Figure 4 that the utilization rate of nitrogen varied seldom and was maintained at approximately seventy-five percent when influent BOD/N value was in a range from 100/5 to 100/2. When BOD/N value was 100/0.94, there wasn't an additional nitrogen source and the nitrogen that the microorganisms required was supplied by wastewater. Here, utilization rate of nitrogen was the lowest and only reached ten percent. Because the nitrogen source in the substrate consisted of  $\text{NH}_4\text{Cl}$  and organic nitrogen under the normal influent conditions with sufficient nitrogen, microorganisms applied  $\text{NH}_4\text{Cl}$  firstly. However, under the condition that influent BOD/N value was 100/0.94, there was no additional  $\text{NH}_4\text{Cl}$  and the microorganisms could not but utilize organic nitrogen as the nutrient for their growth. It meant that at certain low influent BOD/N value (in the experiment it was 100/0.94), microorganisms could not utilize the limited nitrogen source and their metabolism and degradation for organic matter were suppressed seriously.

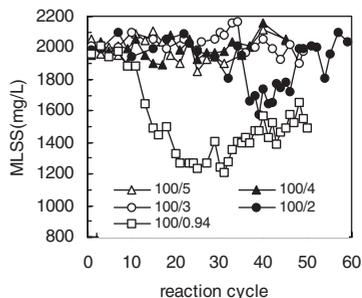
The phosphorus utilization rate was slightly different from that of nitrogen. The results in Figure 5 show that the more serious the degree of nitrogen deficiency, the higher the effluent total phosphorus concentration and correspondingly the lower the phosphorus utilization rate. Thus it could be seen that under the condition that nitrogen content in the influent was insufficient, there were two instances. Firstly, when the degree of nitrogen deficiency wasn't severe (BOD/N values were 100/3 and 100/2 respectively), anabolism activity of microorganisms wasn't influenced observably and limited nitrogen source was applied to synthesize cells and degrade organic matter by microorganisms as much as they could. Secondly, when the degree of nitrogen deficiency was severe (BOD/N value was 100/0.94), activity of microorganisms was suppressed and nitrogen utilization rate decreased rapidly.

The experimental results of the effects of nitrogen deficiency on the removal rate of organic matter are shown in Figure 6. It could be seen from Figure 6 that the effects were not great in spite of the nitrogen deficiency under the conditions that influent BOD/N values were 100/4, 100/3 and 100/2 respectively. The organic matter removal rate was approximate eighty percent. Moreover, there was a big decrease in organic matter removal when influent BOD/N value was 100/0.94.

Application of microorganisms to organic matter was reflected in the increase of the sludge quantity directly. Variations of MLSS concentration at different influent nitrogen content are presented in Figure 7. Under the conditions that influent BOD/N values were 100/5, 100/4 and 100/3, some excess sludge was removed after each cycle in order to maintain the MLSS concentration from 1,900 mg/L to 2,100 mg/L. When influent BOD/N



**Figure 6** Removal efficiency of COD at different influent BOD/N value



**Figure 7** Variation of MLSS at different influent BOD/N value

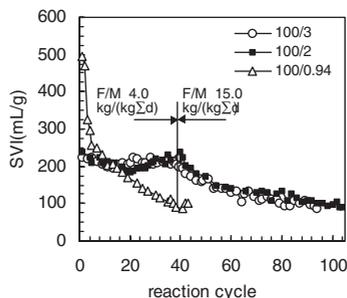
value increased to 100/2, excess sludge amount reduced. However, MLSS concentration could still be maintained at approximately 2,000 mg/L. When influent BOD/N value reached 100/0.94, normal metabolism and growth of microorganism were suppressed. Here, MLSS concentration had a big decrease and was reduced to 1,300 mg/L despite excess sludge not being removed.

#### Control of bulking caused by the deficiency of nitrogen

For non-filamentous bulking occurring at each influent BOD/N value, control methods were carried out at different conditions. The results are shown in Figure 8. In the experiments, non-filamentous bulking occurred at the BOD/N value of 100/3 and 100/2 could not be controlled effectively after the nitrogen source was sufficient. The SVI value had no downtrend after forty cycles. However, when the organic loading was increased to 15 kg/(kg-d), the non-filamentous bulking caused by the excessive growth of viscous *Zoogloea* was controlled effectively.

The characteristics, that *Zoogloea* had a high reservable and accumulable ability and max specific growth rate, were applied to bulking control at high organic loading (Wang *et al.*, 2000). In the experiments the SBR process was applied. The substrate concentration was high in the initial reaction period in that normal *Zoogloea* proliferated rapidly and substituted for viscous *Zoogloea* with high percentage of moisture and settling properties of the sludge got better. The higher organic loading was, more quickly the normal *Zoogloea* proliferated and the more rapidly the non-filamentous bulking came back.

But control of non-filamentous bulking occurring at the influent value BOD/N of 100/0.94 was different from the case mentioned above. The non-filamentous bulking could be controlled effectively at normal organic loading (4.0 kg/(kg-d)) after influent nitrogen content was sufficient despite bulking being the most severe.



**Figure 8** Variation of SVI value during the bulking control period

The writer considers that the reason was at this condition the *Zoogloea* state was different from that of other conditions. Microorganisms could not grow normally because degree of nitrogen deficiency was severe. Compared with other conditions, total amount of microorganisms decreased and viscous substrate with high percentage of moisture secreted by floc forming approached more and more the condition that influent BOD/N was 100/0.94. Therefore, after influent nitrogen content was sufficient, normal *Zoogloea* proliferated rapidly and substituted for viscous *Zoogloea* and settling properties of activated sludge improved.

### Conclusions

Under the condition that influent BOD/N value was 100/4, settling properties of activated sludge were well, effluent suspended substance was reduced and SVI was approximately 70 mL/g. When the influent BOD/N values were 100/3 and 100/2 respectively, non-filamentous bulking caused by viscous *Zoogloea* occurred. Excessive growth of filamentous bacteria was observed at one time under the condition that BOD/N was 100/3. This kind of non-filamentous bulking could be controlled at high organic loading after influent nitrogen source was sufficient. Severe non-filamentous bulking was observed under the condition that influent BOD/N value was 100/0.94. And the bulking could be controlled effectively at normal organic loading after influent nitrogen source was sufficient.

Under the condition that influent BOD/N values were 100/4, 100/3 and 100/2, anabolism of microorganisms wasn't influenced greatly and organic matter removal rate could reach to approximate eighty per cent. However, the activity of microorganisms was suppressed obviously when BOD/N value was 100/0.94.

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