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Fractal characteristics of filamentous bacteria in activated sludge and its significance

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Abstract: On the basis of fractal theory, the fractal characteristics of filamentous bacteria in activated sludge are studied by image dissector system. The results show that the spatial distribution structure of filamentous bacteria in activated sludge has high self-similarity in statistics and the filamentous bacteria have clear phenomenon of fractal growth. The critical fractal dimension values of filamentous bacteria bulking such as Eikelboom 021N, Eikelboom 1701, Sphaerotilus natans and Eikelboom 0041 are determined initially. The fractal dimensions can be taken as a parameter to describe filamentous bacteria of activated sludge quantitatively and bring to light the disorder in appearance and the rule in inherence of filamentous bacteria system.

Key words: activated sludge; filamentous bacteria; fractal; fractal growth; fractal dimension

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Introduction

Researchers in many countries have analyzed massively for the problem of bulking of activated sludge in waste water treatment, particularly the bulking of filamentous bacteria. A large number of filamentous bacteria spread their hyphas out from coacervate of activated sludge and mix to a complex net structure. Palm and Segzin (Palm, 1980; Segzin, 1978) discovered that the critical point for bulking of activated sludge is filamentous bacteria with total length of $10 \mu m/ml$, but their measuring method was too complex for application. Eikelboom (Wang, 1992) put forward a classification of sludge according to the amount of filamentous bacteria and divided them into five types: Ⅰ——almost no filamentous bacteria; Ⅱ——a few; Ⅲ——a certain amount; Ⅳ——a large amount; Ⅴ——excessive filamentous bacteria. Ⅳ and Ⅴ are classified as bulking sludge. It is obvious that this describing method can be applied easily but it is inadequate in quantitative determination and be influenced by experience of identifier. Though the researchers pay a price for the study of filamentous bacteria in activated sludge, the result being of great importance in theory and application has not arisen.

The fractal theory reflects the non-scale and self-similarity of complex natural phenomenon. That is, which means the similarity in statistics of part and part, part and whole on shape, function, information, temporal and spatial distribution, which brings a quantitative technique to describe the natural complex geometric shape. Plantiful information about genesis and development of filamentous bacteria is implicated in their spatial net structure which clearly have stratification and self-similar characteristics. The fractal characteristics of filamentous bacteria in activated sludge are quantitatively analyzed in this paper by means of image dissection and fractal theory.

1 Measuring method of fractal dimension of filamentous bacteria

We developed an image dissector system for the microstructure of activated sludge in order to measure the spatial fractal dimension of filamentous bacteria. The composition of the system and

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their process are shown in Fig. 1. Firstly solution sample (100ml) of the mixed sludge was made and stirred well. Then move a little solution with suction tube to microscopic slide and observe the distribution of filamentous bacteria through microscope. The fractal dimension was determined by box-counting method. The information of filamentous bacteria distribution was transformed into videosignal by video camera, then the videosignal was transformed into digital data by digitizer and stored in storage. The spatial distribution image of filamentous bacteria can be obtained in computer through a set of information processing. At last, the image was covered with squares which the side is ε, there are $N(\varepsilon)$ which grid elements contain filamentous bacteria. When ε changed in [1256] to $\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_n$, a sequence of $N(\varepsilon_1), N(\varepsilon_2), \cdots, N(\varepsilon_n)$ could be obtained, and the fractal dimension D value of filamentous bacteria in activated sludge could be computed by:

$$D = -\lim_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log \varepsilon}. \qquad (1)$$

It is feasible to obtain the fractal dimension D by fitting slope of the straight line section in double-log graph of $\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_n$ and $N(\varepsilon_1), N(\varepsilon_2), \cdots, N(\varepsilon_n)$. The larger D is, the more complex the spatial distribution of filamentous bacteria is.

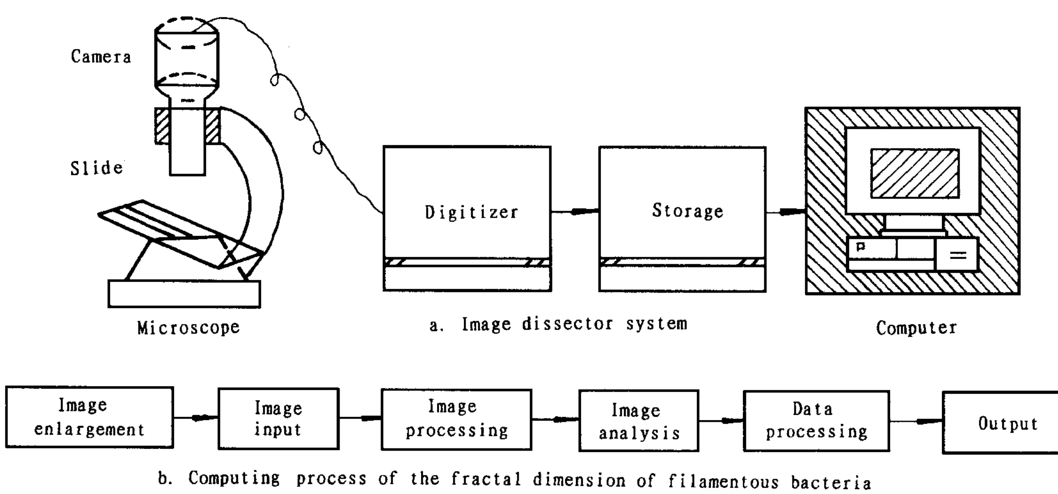

Fig. 1 Quantitative analysis system and working process of filamentous bacteria in activated sludge

2 The fractal characteristic of filamentous bacteria in activated sludge

The development of filamentous bacteria in activated sludge is the main factor which controls the subsidence of sludge. Owing to different kinds of filamentous bacteria varying in shape, it is difficult to describe quantitatively for filamentous bacteria. Fractal theory gives a probable solution to this problem. According to the above-mentioned experimental method, we collected 107 bulking sludge samples. The fractal dimensions of eight typical kinds of filamentous bacteria (adopting Eikelbooms classification method) in steady condition were determined and shown in Table 1. The double-log graphs of ε and $N(\varepsilon)$ are shown in Fig. 2.

There is a clear segment of straight line in the double-log graphs of ε and $N(\varepsilon)$ in Fig. 2. That represents the self-similarity and typical fractal characteristic of the spatial distribution of filamentous bacteria in activated sludge. By making a comparison between *SVI* values of sludge samples and fractal dimensions of filamentous bacteria (Table 1), we could find out that *SVI* value and expansibility of sludge increase when the fractal dimensions of filamentous bacteria rise. The general law is obvious although these results were determined in variant sedimental stages for variant samples.

Table 1 Statistics of the fractal dimension of typical filamentous bacteria and *SVI* (ml/g) value

Bacteria type	Fractal dimension		*SVI* value, ml/g		Waste water model	Sample amount
	Range	Average	Range	Average		
Eikelboom 1701	1.611—1.784	1.727	457—463	576	Paper factory	22
Sphaerotilus natans	1.541—1.632	1.581	386—521	416	Food factory	17
Eikelboom 1863	1.382—1.528	1.455	123—268	185	Petrochemical factory	9
N. limicola. I	1.341—1.511	1.496	93—241	168	Petrochemical factory	6
Thiotnrix	1.312—1.477	1.439	107—156	148	Waste water mixing factory	8
Eikelboom 0041	1.589—1.707	1.675	329—513	462	Beer factory	14
Eikelboom. 0961	1.411—1.457	1.423	121—254	192	Petrochemical factory	10
Eikelboom 021N	1.609—1.838	1.688	424—612	511	Meat processing factory	21

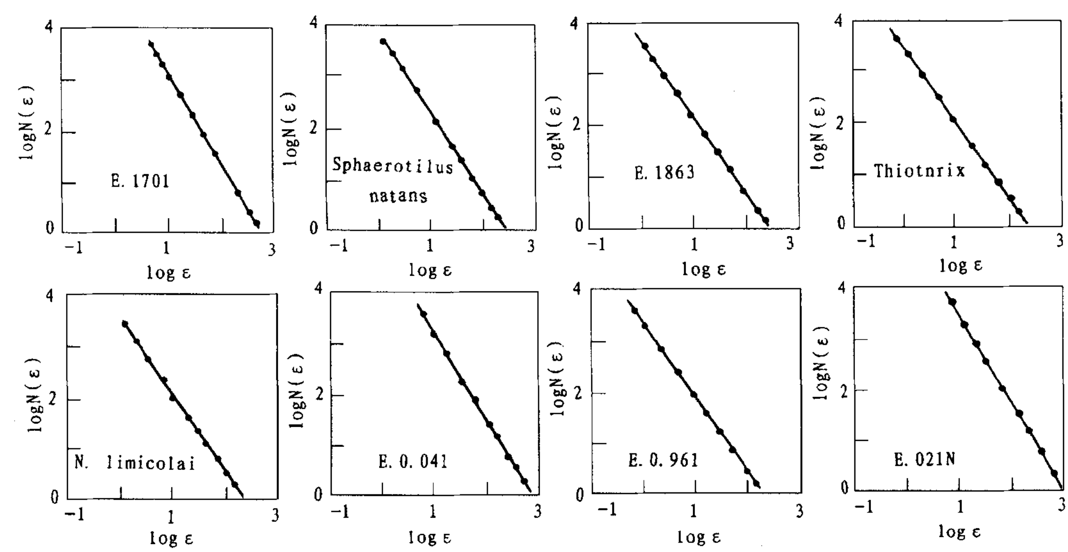

Fig. 2 The correlation graphs between ε and $N(\varepsilon)$ of typical spatial distribution of filamentous bacteria

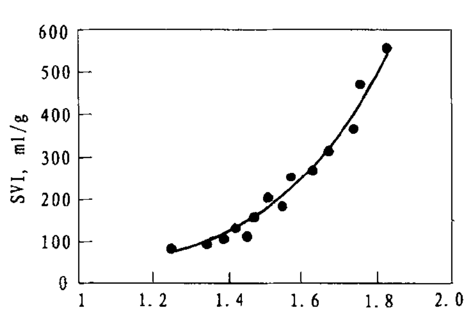

Fig. 3 The correlation graph between the fractal dimensions of filamentous bacteria and the *SVI* value of sludge

We found, from attentive observation in laboratory test, although the expansibility of activated sludge is controlled by the dominant filamentous bacteria, in fact it is resulted from the common action of several kinds of filamentous bacteria. So, it would be more valuable in application to determine the fractal dimensions of all kinds of filamentous bacteria in each sample and to analyze the relation between fractal dimension and *SVI* values. We have determined the fractal dimensions of mixed filamentous bacteria and *SVI* value of sludge for 15 groups of samples, as shown in Fig. 3. The relation model was developed with regression analysis, as follows:

$$SVI(\mathrm{ml/g}) = 0.8599\exp(3.5372D). \quad (2)$$

3 The fractal characteristics of growth process of filamentous bacteria

The growth of filamentous bacteria in activated sludge is a process from simple state to complex state. In Table 2, the fractal dimensions and *SVI* (ml/g) values of several typical filamentous bacteria at different growth time are shown. Eikelboom 021N grow fast and make the sludge bulking quickly. It grows at the most speed on the 2nd or 3rd day and the fractal dimension increases from 1.12 to 1.825, then comes to a stable value around 1.83, and the *SVI* value increases from 54 (ml/g) to 807 (ml/g). It is distinct that the Eikelboom 1701 and Sphaerotilus natans grows more slowly than the Eikelboom 021N bacteria even though they also cause sludge to bulk, their fractal dimensions change slowly and comes to a stable value around 1.6 eight days later, also their *SVI* values change slowly. So, the self-similarity of the growth of filamentous bacteria in activated sludge shows that ontogenesis of filamentous bacteria is the fast repeat of microorganism species evolution, which is typical phenomenon of fractal growth. The fractal dimensions proved the nonlinear increasing process of microorganisms in activated sludge. The larger the dimension values are, the more complex the spatial distribution characteristics of the filamentous bacteria are with time going, and the bulking of activated sludge becomes stronger. The fractal dimension reflects the complexity of the stochastic evolution of its functional pattern and reveals the external disorder characteristics and the internal regularity of microorganism growth process in activated sludge.

Table 2 The fractal characteristics in growing period of filamentous bacteria

Time, d	Eikelboom 021N		Eikelboom 1701		Sphaerotilus natans	
	D	*SVI*, ml/g	*D*	*SVI*, ml/g	*D*	*SVI*, ml/g
0.5	1.120	54	1.151	61	1.164	66
1	1.347	83	1.261	69	1.273	76
1.5	1.683	416	1.393	85	1.359	88
2	1.817	625	1.414	94	1.421	114
3	1.825	747	1.526	79	1.487	152
5	1.829	788	1.613	602	1.574	458
8	1.834	807	1.627	631	1.601	527

4 Critical fractal dimension features of filamentous bacteria bulking in activated sludge

Harmful as filamentous bacteria bulking in activated sludge is, concurrently filamentous bacteria form the framework of the flocculating sludge, and it is advantageous to strength of activated sludge. Apparently too few filamentous bacteria lower the shear strength of the flocculent sludge and bring about turbidity of the discharge water from sewage treatment plant. Ninety-one groups of activated sludge were sampled right at the beginning of bulking in sewage treatment plants and in middle-sized test devices. Critical fractal dimension values were preliminary determined from the sludge bulking caused by several typical filamentous bacteria through measuring the fractal dimension values and *SVI* values at the same time (Table 3). We can know from the Table 3, although certain difference exists among the inter-region of critical fractal dimension values representing sludge bulking aroused by Eikelboom 021N, Eikelboom 1701, Sphaerotilus natans and Eikelboom 0041, rapid bulking would occur once fractal dimension value amounts to about 1.5. It could be initially ascertained that the critical fractal dimension value scope showing activated sludge bulking is approximately 1.45—1.50. Fractal dimension can be used as a quantitative index describing filamentous bacteria in conventional glass test of activated sludge. The results mentioned above derived from experiments on filamentous bacteria growth. However, excessive growth of filamentous bacteria is closely related to the components of waste water, concentration of dissolved oxygen in exposure tank and concentration of real dissolved plasma in microorganisms. Further classification study on these problems is intended to be discussed in detail in other papers.

Table 3 Statistics of critical fractal dimension values of filamentous bacteria in activated sludge bulking

Bacteria type	Range of critical fractal dimension	Average critical value	*SVI* value, ml/g	Sample amount
Eikelboom 021N	1.437—1.522	1.501	146—166	20
Eikelboom 1701	1.461—1.528	1.513	151—173	31
Sphaerotilus natans	1.422—1.493	1.461	148—161	18
Eikelboom 0041	1.436—1.502	1.471	143—158	22

5 Conclusion and discussion

Summarily, some cognition can be achieved, as follows:

The spatial distribution structure of filamentous bacteria in activated sludge has self-similarity in statistics. Its fractal structure takes shape from specific dynamic processes in unbalanced conditions in the filamentous bacteria system, and the fractal characteristics reflect the mechanism of formation process simultaneously. Therefore, fractal dimension can be used as a quantitative parameter describing filamentous bacteria, and the higher the fractal dimension value is, the higher degree the self-organization of filamentous bacteria is, the higher stage its evolution is in and the higher extent the sludge bulking becomes as well.

It can be seen from fractal theory that if fractal structure exists in the growth of filamentous bacteria, the length of microorganism should be expressed as $L = N(\varepsilon)\cdot\varepsilon = A_0\varepsilon^{1-D}$. This equation indicates L (length) relies on measured scale ε, i.e., the small scale would produce long length. Provided that the plane length were converted into spatial surface area, larger surface area value would be expected. Consequently, the surface are of filamentous bacteria in activated sludge is much more enormous than that of bacteria mass so as to result in sludge bulking, which coincides with the ratio of surface area to capacity hypothesis about sludge expansion.

A clear phenomenon of fractal growth takes place in the growing process of filamentous bacteria in activated sludge. Namely, the process has temporal fractal characteristics.

The best approach putting fractal into the study of sludge filamentous bacteria is to regard fractal dimension as a parameter in statistics. According to particular sewage treating environment, *SVI* values and other evaluating indexes of different bulking sludge samples were compared one another to seek valuable and empirical critical indexes to direct activated sludge bulking control and experiments.

In brief, fractal theory is an effective method describing complex phenomena, but its study on applications in activated sludge has not yet set out and further exploration is expected. It is believed that new understandings in reality as well as in theory will be obtained with the investigation and study deep going.

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