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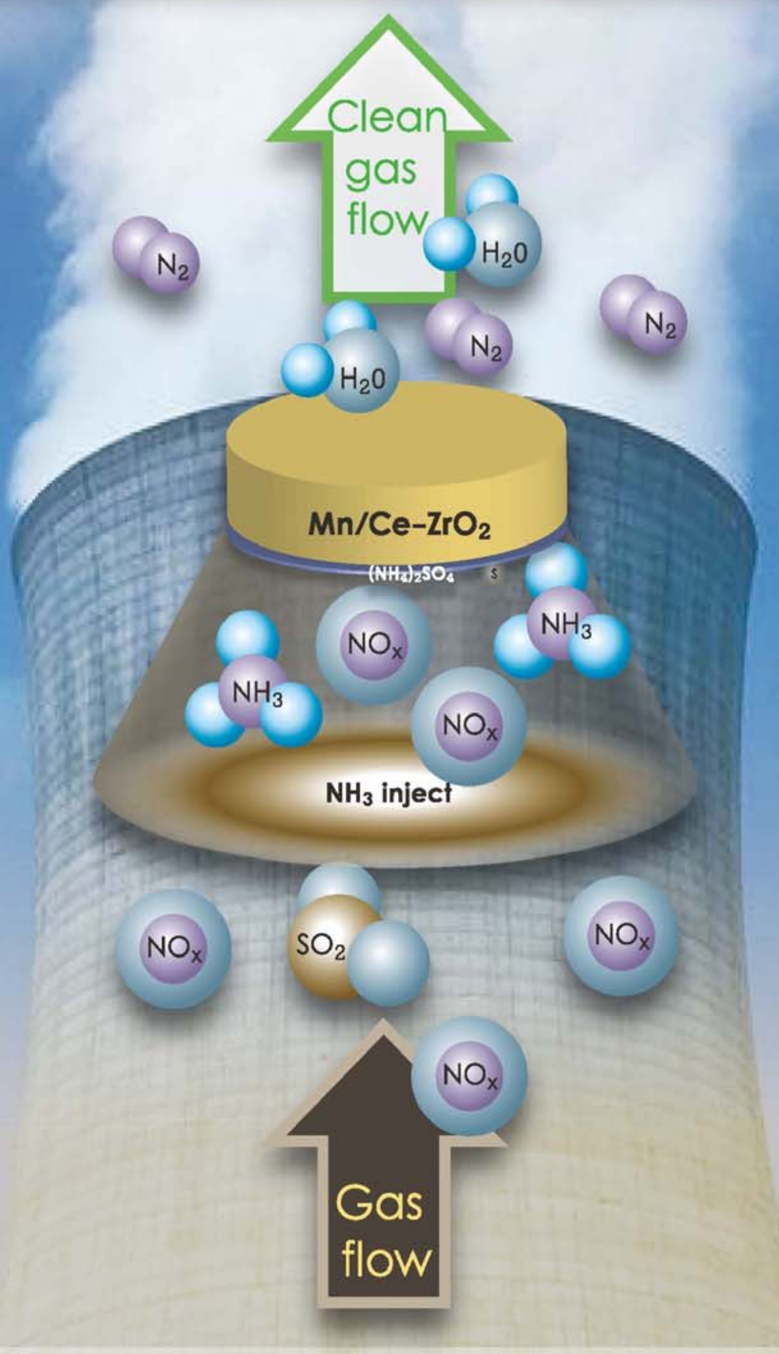

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Analysis of aerobic granular sludge formation based on grey system theory

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Abstract

Based on grey entropy analysis, the relational grade of operational parameters with aerobic granular sludge's granulation indicators was studied. The former consisted of settling time (ST), aeration time (AT), superficial gas velocity (SGV), height/diameter (H/D) ratio and organic loading rates (OLR), the latter included sludge volume index (SVI) and set-up time. The calculated result showed that for SVI and set-up time, the influence orders and the corresponding grey entropy relational grades (GERG) were: SGV (0.9935) > AT (0.9921) > OLR (0.9894) > ST (0.9876) > H/D (0.9857) and SGV (0.9928) > H/D (0.9914) > AT (0.9909) > OLR (0.9897) > ST (0.9878). The chosen parameters were all key impact factors as each GERG was larger than 0.98. SGV played an important role in improving SVI transformation and facilitating the set-up process. The influence of ST on SVI and set-up time was relatively low due to its dual functions. SVI transformation and rapid set-up demanded different optimal H/D ratio scopes (10–20 and 16–20). Meanwhile, different functions could be obtained through adjusting certain factors' scope.

Key words: aerobic granular sludge; grey system theory; operational impact factor; granulation process

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Introduction

Aerobic granular sludge has a dense microbial structure, high bioactivity, excellent settling ability, and is capable of dealing with high-strength wastewater that contains organics, nitrogen and phosphorus substances (Jiang et al., 2002; Liu and Tay, 2004; Moy et al., 2002; Zheng et al., 2005). Compared to traditional activated sludge treatment approaches, aerobic granular sludge technology with sequencing batch reactor (SBR) is now considered to be a new and promising wastewater treatment approach since it could cut the investment and operating costs as well as space requirements (Lee et al., 2010; Liu et al., 2010; Mosquera-Corral et al., 2005). However, the factors that impact the granulation process are numerous and the influencing mechanism is obscure, which makes it difficult to control and predict the set-up process for aerobic granular sludge, and further limits the practical application of this technology.

The grey system theory (GST) method was proposed by Deng Julong in 1982; it included grey relational analysis (GRA) and grey models (Pai et al., 2007). GRA, denoted by the grey relational coefficients (GRCs) and grey entropy relational grade (GERG), could investigate the relationship between reference sequences and compared sequences. The GRA approach could quantify the obscure and complex relationship among multi-parameters, and distinguish the impact order of the chosen parameters on a certain reference parameter, which is especially suitable for cases that contain a small amount of representative data. Generally speaking, as a powerful analysis technique, the GST method is able to cope with complex, uncertain or fragmented systems by means of a reliable calculation process (Hsiao and Tsai, 2004).

GST theory had been applied to a variety of fields, such as engineering classification and control systems (Chang et al., 2000; Peng and Kirk, 1999) as well as environmental systems (Li et al., 2003). However, no research articles on the cultivation of aerobic granular sludge based on this theory have been reported. Although the parameters that affect the characteristics of aerobic granular sludge are complicated, GST provides an alternative to quantitatively describe their relationships. In this article, based on data obtained from different studies, the GERG generated from a series of correlation function calculations was used to describe the relational grade and reflect the impact order of each chosen operational factor on certain aerobic granulation indicators, thereby, distinguishing the key impact factors and providing the optimal scope. It is hoped that

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the information generated from this article could be useful to optimize the cultivation of aerobic granules in SBRs.

1 Research methods

1.1 Reference parameters and operational impact factors

For the set-up process of an aerobic granular sludge system, sludge volume index (SVI) could effectively indicate the granulation degree and the granular sludge's settling ability, and the granulation speed could be intuitively expressed by the set-up time. Both SVI and set-up time would be eventually influenced, whether directly or not, by the operational impact factors. Hence, SVI and set-up time were chosen as the reference parameters.

Aerobic granulation is closely related to operating conditions. Up to now, published results indicate that the operational factors that play a significant role in influencing the granulation process in the SBR mainly consist of five parameters: settling time (ST), superficial gas velocity (SGV), aeration time (AT), height/diameter (H/D) ratio and organic loading rates (OLR). ST serves as a hydrodynamic selection pressure by keeping the sludge with good setting ability in the reactor and washing out light flocs (Qin et al., 2004). The hydrodynamic shear force, caused by aeration and generally measured as SGV, would stimulate bacteria to secrete more polysaccharides (Tay et al., 2001b). Moreover, it provides a detachment pressure to force the cells to detach from the granule surface until a dynamic equilibrium between detachment and biomass growth is reached, and imposes the dissolved oxygen concentration (Mosquera-Corral et al., 2005; Zhang et al., 2011). For AT, on the one hand, it reflects the length of the hydrodynamic shear force, on the other hand, its period is indirectly associated with the starvation time. As reported, the nutrients would be consumed within 30 min of aeration (Li et al., 2006), leaving a long period of starvation time at longer AT. A certain period of starvation time could balance the concentration of extracellular polymeric substances (EPS) and initiate the aerobic granulation (Li et al., 2006). In SBR, a high H/D ratio could select for better settling ability of granules due to an improved hydrodynamic selection pressure (Beun et al., 1999, 2002). Different OLR would influence the growth rate of the microorganisms, thereby providing a microbial selection pressure for aerobic granulation (Li et al., 2008; Moy et al., 2002). Hence, the five factors mentioned above were chosen as operational impact factors.

1.2 Data acquisition

To avoid unnecessary errors, the chosen aerobic granular sludges were all cultivated in SBRs, with the exchange ratio of liquid volume of 50% at the end of each cycle, and the operating cycle only contained four phases: feeding, aeration, settling and efflux. Meanwhile, the inoculated sludge was flocculent sludge. SVI was defined as SVI_{30} here. **Table 1** shows the original data from different references (Adav et al., 2010; Chen et al., 2008; Guo et al., 2011; Kong et al., 2009; Li et al., 2006, 2008; Liu et al., 2007; Liu and Tay, 2008; Mosquera-Corral et al., 2011; Wang et al., 2007).

1.3 Grey system theory

In grey relational space, a system contains many series with k entities:

$$X_i^{0*} = \left\{X_i^{0*}(k)\,|\,i = 1, 2, \cdots, m, k = 1, 2, \cdots, n\right\} \tag{1}$$

$$X_j^{*} = \left\{X_j^{\ *}(k)\,|\,j = 1, 2, \cdots, r, k = 1, 2, \cdots, n\right\} \tag{2}$$

where, $X_i^{\ 0*}$ is the reference sequence, $X_j^{\ 0*}$ is the compared sequence, m, r and n stand for the number of the reference parameter, compared parameter, and total experiments, respectively. In this study, SVI and start-up time were chosen as reference parameters, compared parameters consisted of ST, SGV, AT, H/D ratio and OLR, and the data were acquired from 18 experiments. Thus, m = 2, r = 5 and n = 18.

Since the units of the sequences varied widely from each other, the series data were subjected to pre-processing normalization as shown below before calculating the GRCs.

$$X_i^{0}(k) = \frac{X_i^{0*}(k)}{\frac{1}{n}\sum\limits_{k=1}^{n} X_i^{0*}(k)} \tag{3}$$

Table 1 Original experimental data

	Sequence number																	
	1^{a}	2^{b}	3^{b}	4^{b}	5^{c}	6^{d}	7^{e}	8^{e}	9^{f}	10^{g}	11^{g}	12^{g}	13^{h}	14^{h}	15^{h}	16^{h}	17^{i}	18^{j}
H/D ratio	24	20	20	20	2.5	30	10	10	20	13.3	13.3	13.3	24	16	8	4	20	20
AT (min)	220	78	228	468	171	169	225	225	215	230	230	230	227	227	227	227	223	236
SGV (cm/sec)	3	2.4	2.4	2.4	1.6	2.5	3.2	2.4	3.4	2.4	2.4	2.4	2.5	2.5	2.5	2.5	1	2.4
OLR (kg COD/(m^3·day))	3	8.0	3	1.5	1.8	8	6	6	9	1.5	3	4.5	3	3	3	3	6	6
ST (min)	10	2.0	2	2	3	5	5	5	5	2	2	2	3	3	3	3	7	1
SVI_{30} (mL/g)	65	60	30	50	40	32	27	41	34	38.2	43	57	49	43.2	57.3	57.5	53	52
Set-up time (day)	35	30	33	35	58	13	40	40	40	50	25	12	35	35	35	35	35	60

[a] Liu et al., 2007; [b] Liu and Tay, 2008; [c] Mosquera-Corral et al., 2011; [d] Li et al., 2006; [e] Chen et al., 2008; [f] Adav et al., 2010; [g] Li et al., 2008; [h] Kong et al., 2009; [i] Guo et al., 2011; [j] Wang et al., 2007.

$$X_j(k) = \frac{X_j^*(k)}{\frac{1}{n}\sum_{k=1}^{n} X_j^*(k)} \tag{4}$$

Then, the reference sequence and compared sequence transform to the following forms:

$$X_i^0 = \left\{X_i^0(k)\,|\,i = 1, 2, k = 1, 2, \cdots, n\right\} \tag{5}$$

$$X_j = \left\{X_j(k)\,|\,j = 1, 2, \cdots, 5, k = 1, 2, \cdots, n\right\} \tag{6}$$

The GRCs calculation between the reference sequence $X_i^0(k)$ and the compared sequence $X_j(k)$ at point k is defined as:

$$\zeta_{ij}(k) = \frac{\min\limits_j \min\limits_k \left|X_i^0(k) - X_j(k)\right| + \rho \max\limits_j \max\limits_k \left|X_i^0(k) - X_j(k)\right|}{\left|X_i^0(k) - X_j(k)\right| + \rho \max\limits_j \max\limits_k \left|X_i^0(k) - X_j(k)\right|} \tag{7}$$

where, $\rho \in [0, 1]$, acting as the coefficient of $\max\limits_j \max\limits_k \left|X_i^0(k) - X_j(k)\right|$, is the distinguishing coefficient. Since $\max\limits_j \max\limits_k \left|X_i^0(k) - X_j(k)\right|$ is used to describe the integrity of a system, ρ is typically taken as 0.5 to control the resolution between $\max\limits_j \max\limits_k \left|X_i^0(k) - X_j(k)\right|$ and $\min\limits_j \min\limits_k \left|X_i^0(k) - X_j(k)\right|$.

Actually, GRC is used to indicate the relational grade between the reference sequence X_i^0 and the compared sequence X_j^* at point k. As the optimal scope of an impact factor is defined as the range of the original value whose GRC is larger than a certain value, it could be obtained through comparing the GRC of j on i. To take all impact factors' GRC value into account, the minimal GRC value was set at 0.75, since all the impact factors' optimal scopes could be obtained under this condition, and certain impact factor's optimal scopes would be narrowed down when the minimal GRC value was larger than 0.75. Thus, 0.75 was chosen to be the minimal GRC value.

To make full use of the abundant information supplied by GRCs and avoid being misled by larger GRCs, GERG is adopted to determine the key operational impact factors and rank them by relational grade.

The map value of the GRCs distributed map is the relational coefficient distribution density (p_{ij}), which is given as:

$$p_{ij}(k) = \frac{\zeta_{ij}(k)}{\sum_{k=1}^{n} \zeta_{ij}(k)} \tag{8}$$

The grey relational entropy of the operational impact factor j on the reference parameter i can be calculated as:

$$S_{ij} = -\sum_{k=1}^{n} \left[p_{ij}(k) \ln p_{ij}(k)\right] \tag{9}$$

The GERG (E_{ij}) for the operational impact factor j on the reference parameter i is defined as:

$$E_{ij} = \frac{S_{ij}}{S_{\max}} \tag{10}$$

where, $S_{\max}$ is the sequence maximum entropy, which is a constant ($\ln n$) that only associates with the number of the element when the value of elements contained in each series equals to each other. Strong relevance between the reference sequence and compared sequence corresponds to large E_{ij}, and the key operational impact factor and the influence order can be acquired by comparing the calculated GERG of each compared sequence.

2 Results and discussion

2.1 Sludge volume index analysis

In SBRs, the SVI of active sludge flocs mainly fluctuated between 80 and 150 mL/g. A decrease in SVI, driven by the combined stress supplied by all the factors, indicates that the structure of the aggregates becomes more dense and compact. In other words, lower SVI means settling ability is being effectively improved. Therefore, SVI is an effective measure indicator to describe the degree of granulation in the process. In this part, the reference sequence was SVI (X_1^{0*}), and the compared sequences were: H/D ratio (X_1^*, $j = 1$), AT (X_2^*, $j = 2$), SGV (X_3^*, $j = 3$), OLR (X_4^*, $j = 4$) and ST (X_5^*, $j = 5$). GRCs, GERG, and the optimal scope of each operational impact factor on SVI are listed in **Tables 2** and **3**, respectively.

According to the GST, the GRCs reflect the relational grade of the reference sequence and compared sequence at point k. A large GRC corresponds to a high relational grade. As **Tables 2** and **3** show, the GRC of SGV at 2.4 and 3.0 cm/sec were as high as 0.9515 and 0.7884, and the highest GRC value on SVI (0.9515) was SGV at 2.4 cm/sec, which indicated that a relatively high level of SGV (2.4–3.0 cm/sec) could efficiently improve the aerobic granular sludge's settling ability and contribute greatly to reduce SVI. Additionally, the optimal scope of AT, OLR, ST and H/D were 169–227 min, 3–6 kg COD/(m^3·day), 2–3 min and 10–20, respectively.

The calculated GERGs of the five factors, displayed in **Table 3**, were all above 0.98, implying that the five factors chosen above were all key impact factors for the aerobic granulation process. As E_{13} (0.9935) > E_{12} (0.9921) > E_{14} (0.9894) > E_{15} (0.9876) > E_{11} (0.9857), it could be

Table 2 GRCs of SVI and set-up time

	Sequence number																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SVI																		
H/D ratio	0.8902	0.9315	0.5348	0.8101	0.4908	0.3676	0.9541	0.7210	0.5738	1.0000	0.8751	0.6299	0.6189	0.9218	0.4798	0.4071	0.8779	0.8541
AT	0.6134	0.4177	0.6563	0.4085	0.8661	0.9287	0.6252	0.8660	0.7621	0.7836	0.8899	0.7627	0.9154	0.9109	0.7461	0.7426	0.8133	0.8982
SGV	0.7884	0.6875	0.6717	0.8796	0.7613	0.6732	0.4840	0.8778	0.5091	0.8309	0.9515	0.7226	0.9427	0.8853	0.7642	0.7605	0.4817	0.8330
OLR	0.4849	0.5715	0.9617	0.4797	0.5939	0.3789	0.4688	0.5924	0.3438	0.5849	0.7335	0.7638	0.6370	0.7301	0.5502	0.5482	0.7651	0.7470
ST	0.3350	0.4784	0.8794	0.5642	0.9530	0.4985	0.4619	0.5813	0.5148	0.7155	0.6451	0.5013	0.7401	0.8688	0.6254	0.6230	0.4651	0.4461
Set-up time																		
H/D ratio	0.6327	0.6860	0.7328	0.7677	0.3810	0.3731	0.6463	0.6463	0.8715	0.6159	0.8698	0.6439	0.6327	0.9759	0.6541	0.5535	0.7677	0.6800
AT	1.0000	0.6476	0.9078	0.4493	0.5120	0.6990	0.8865	0.8865	0.8493	0.7075	0.7355	0.5672	0.9666	0.9666	0.9666	0.9666	0.9854	0.5903
SGV	0.7842	0.8562	0.9303	0.9873	0.4821	0.5743	0.8167	0.8773	0.7598	0.6808	0.7667	0.5856	0.9446	0.9446	0.9446	0.9446	0.6149	0.5681
OLR	0.7542	0.4782	0.7912	0.5864	0.4245	0.3819	0.7842	0.7842	0.4917	0.4607	0.9845	0.5667	0.7542	0.7542	0.7542	0.7542	0.6992	0.7447
ST	0.3337	0.7617	0.7113	0.6812	0.5338	0.4679	0.7695	0.7695	0.7695	0.5172	0.8638	0.8044	0.8623	0.8623	0.8623	0.8623	0.4828	0.3919

Table 3 Importance order, GERG, and optimal scope of each factor on SVI and set-up time

Parameter	SVI			Parameter	Set-up time		
	Importance order	E_{1j}	Optimal scope		Importance order	E_{2j}	Optimal scope
SGV (cm/sec)	1	0.9935	2.4–3.0	SGV (cm/sec)	1	0.9928	2.4–3.4
AT (min)	2	0.9921	169–227	H/D ratio	2	0.9914	16–20
OLR (kg COD/(m^3·day))	3	0.9894	3–6	AT (min)	3	0.9909	215–228
ST (min)	4	0.9876	2–3	OLR (kg COD/(m^3·day))	4	0.9897	3–6
H/D ratio	5	0.9857	10–20	ST (min)	5	0.9878	2–3

concluded that the operational impact factors' influence order on SVI was SGV > AT > OLR > ST > H/D ratio, which meant that SGV can be listed in first place among the key impact factors associated with the active sludge transformation and granulation process most closely.

2.1.1 Superficial gas velocity

The aerobic granulation process experiences the adhesion phase first, and the bacteria metabolism (e.g. the production of EPS) then promotes the adhesion process (Hermansson, 1999). SGV provides the essential environment for this phase as the air introduced at the bottom of the reactor would enhance the turbulence of the mixed liquid, and strengthen the interaction between the gas and liquid phases. Additionally, under high hydrodynamic shear force, cells also secrete more sticky polysaccharide EPS (Tay et al., 2001a). In short, all of the conditions created by SGV played positive roles in facilitating the adhesion of the aggregates.

Subsequently, SGV works as a modifier along with the granulation process. Under given conditions, high hydrodynamic stress could reduce substrate transfer resistance into the granules (Lee et al., 2010), enhance the activity of the inner microorganisms and avoid the cavities caused by cell autolysis. Meanwhile, at the outside of the granule, the detachment force drives fragments departing from the granule surface, and makes the granules become more dense and compact. The final matured aerobic granules with a spherical outer-shape and a stable size indicated that the balance between the growth of the bacteria and the detachment force was achieved.

Up to now, it has been widely accepted that high SGV above 1.0–1.2 cm/sec was a requisite factor to ensure the successful granulation of active sludge. Tay et al. (2001a) found that flocs dominate in the SBR when SGV was less than 0.3 cm/sec, while aerobic granular sludge occurred and gradually became mature when SGV was larger than 1.2 cm/sec. Although aerobic granules were successfully obtained under low SGV (0.63 cm/sec) (Wan et al., 2009), the operational condition was quite different from the traditional SBRs since an anoxic phase was added before aeration, which made the reaction mechanism in their SBR more complex, and consequently led to a different granulation process. However, SGV should not be set at a high level either; when SGV was 5.3–7.08 cm/sec, the larger hydraulic shear stress made the sludge experience the morphology of floc-part particle-floc, and the sludge ultimately disintegrated (Liu et al., 2011). Since SVI was closely related to the formation and granulation grade of the aerobic granular sludge as discussed above, in SBRs, SGV thus dominated the transformation trend of the SVI, which distinguished it from other key impact factors.

2.1.2 Aeration time and organic loading rate

AT and OLR were listed in the second and third place, and the optimal scope was 169–227 min and 3–6 kg COD/(m^3·day), respectively, illuminating that short AT or low OLR was not appropriate for SVI reduction. As discussed above, the hydrodynamic shear force generated from aeration significantly influences the granulation process. In addition, according to Li et al. (2006), in the initial adhesion stage, the metabolism of microorganisms was active as the nutrient supply was abundant compared with the relatively low biomass concentration; as a consequence, plenty of EPS would be secreted. The result generated from their study showed that the protein EPS strongly and positively correlated with surface negative charge, with correlation coefficient r of 0.91, and both protein and carbohydrate EPS strongly and negatively correlated with relative hydrophobicity (r = –0.98, –0.99). In order to enhance hydrophobicity and reduce surface negative charge for aerobic granulation at the first adhesion phase, the excess amount of EPS should be consumed to keep it to a reasonable amount. When the adhesion period was finished, EPS at moderate levels worked as a matrix for the granulation process. As an anaerobic environment was initially unavailable, it was the starvation time that acted as an essential trigger to reduce the production of EPS, but short AT or low OLR corresponded to a short starvation time, and would eventually frustrate the granulation process. However, both AT and OLR should not be set at high level either. As is known, the nutrient would be depleted within a short period, leaving a long starvation time during the rest cycle if AT was too long. In the meantime, an immoderate modification process would also block the nutrient passage of the formed granules, and under such conditions, the organisms residing in the granules would consume the matrix EPS excessively and slash the density of the granules, perhaps even leading to the cells' autolysis. Consequently, this would result in a loosened structure and bad settling ability. For OLR, a high rate favored the growth of heterotrophic microbes, which contributed to irregular structure (Moy et al., 2002), and further impeded the granulation process. Therefore, to obtain better conditions for granulation, AT and OLR needed to be adjusted to certain levels.

2.1.3 Settling time

The relational grade of ST with SVI was relatively low due to its seemingly contradictory dual function. Although the light flocs could be effectively washed out when the ST was short, a huge loss of sludge and newly formed aggregates made the biomass per volume decrease seriously as the initial formation of the granule was slow, consequently leading to OLR increment, which might be likely to cause sludge bulking during long operation. On the contrary, long ST was also unfavorable for granulation as it could not efficiently supply biological selection pressure to screen heavy aggregates with good settling ability. Perhaps these were the reasons why the influence of ST on SVI was relatively inferior compared to that of SGV, AT and OLR. However, this did not mean that its influence should be neglected, as its GERG was still as high as 0.9876. Actually, short ST was the decisive factor responsible for aerobic granulation. Qin et al. (2004) indicated that during an aerobic granulation process, SVI was indeed determined by the degree of aerobic granulation in the process. Moreover, SVI was closely related to the settling time, and a relative high hydrodynamic selection pressure supplied by short ST was necessary in particular.

2.1.4 H/D ratio

By contrast, the GERG of H/D ratio on SVI was the smallest one. With a given ST, a high reactor H/D ratio demanded that the aggregates have a relative fast settling velocity in order not to be washed out of the reactor, and it was reported that the minimal settling velocity needed to be above 10 m/hr for granulation (Beun et al., 2002). However, the inoculated sludge mainly consisted of flocs along with the seed, so that under a high H/D ratio, the newly formed aggregates were not dense or large enough to be stable, and in order to remain in the reactor, they tangled with flocs occupying a lot of space but with light mass compared to the granules, and as a result, obstructed the reduction of SVI. Thus, no matter how high the H/D ratio was set at the beginning, there was relatively low influence on SVI. Kong et al. (2009) proposed and confirmed this assumption as they successfully developed aerobic granules with similar physical properties in four reactors with different H/D ratios of 24, 16, 8 and 4, and the SVI of the four reactors mainly fluctuated between 40–50 mL/g. In any case, an excessively high reactor H/D ratio was basically unfeasible in pilot or full-scale reactor operation as well.

2.2 Set-up time analysis

In this Section, the reference sequence was set-up time: X_2^{0*}, and the compared sequences were the same as mentioned in Section 2.1.

According to the GRCs listed in **Table 2**, the optimal scope of SGV, H/D ratio, AT, OLR and ST was 2.4–3.4 cm/sec, 16–20, 215–228 min, 3–6 kg COD/(m^3·day), and 2–3 min, respectively. The GERGs of the five factors were also larger than 0.98, with E_{23} = 0.9928, E_{21} = 0.9914, E_{22} = 0.9909, E_{24}= 0.9897 and E_{25} = 0.9878 (**Table 3**), indicating that, for the set-up time, the chosen factors were all key impact factors as well, and the influence sequence in decreasing order was SGV > H/D > AT > OLR > ST. The SGV still occupied the first place here.

The optimal scope of H/D ratio, AT and OLR reflected the fact that keeping these factors in a certain range was necessary for rapid aerobic granulation. Although aerobic granular sludge also formed at 1.05–1.68 kg COD/(m^3·day), the whole granulation process consumed one entire year, which was thoroughly unsuitable for practical application since its set-up time was too long (Wang et al., 2009). Similarly, ST remained listed in the last place due to its contradictory functions as discussed above. However, its GERG was still as high as 0.9878, illustrating that the influence of ST should not be neglected. When ST was short, the organisms automatically adjusted their metabolism manner, increased the relative hydrophobicity of cell surfaces and further enhanced the cell aggregation. As has been reported (Gao et al., 2011), the granulation process was rapid under short ST, and the matured granules showed a better settling property and higher storage stability.

As shown in **Table 3**, except for H/D ratio, the impact order of SGV, AT, OLR and ST on set-up time was same as for SVI. The relational grade of H/D ratio on set-up time was stronger than for SVI, and the optimal scope was larger as well (16–20 and 10–20), which meant that, compared to SVI, a relatively high H/D ratio was beneficial for rapid granulation. Under certain ST, a high H/D ratio provided more collision opportunities for microbial cells to aggregate. Moreover, aided by shear force, a high H/D ratio extended the modification length for newly formed aggregates, and in the meantime, provided biological pressure to wash out the light flocs (Kong et al., 2009), and as a consequence, promoting the formation of granules. Beun et al. (2002) proposed that the SBAR should have a relatively high H/D ratio for practical application since a high ratio could improve selection of granules by the difference in settling velocity. Moreover, without an external settler, a high H/D led to a small footprint reactor, making efficient use of the SBR volume.

The results generated in this article mainly focused on the aerobic granules which were cultivated under certain conditions (mentioned in Section 1.2). As the aerobic granular sludge was mainly cultivated under such conditions, it was worth distinguishing the priority and the optimal scope of the major impact operational factors for aerobic granulation process under this cultivation condition.

To acquire granules with certain functions, the result generated from this article could act as a reference. For instance, much attention should be paid to SGV, OLR, ST, H/D ratio and AT when SVI and/or set-up time are concerned. However, each impact factor and its adjusting scope need to be chosen separately since different impact factors and optimal scopes corresponded to different SVI and set-up time.

3 Conclusions

Grey system theory was shown to be suitable for assessing the priority and providing the optimal scope of each operational impact factor with respect to aerobic granulation process indicators. For SVI and set-up time, the influence order were SGV > AT > OLR > ST > H/D and SGV > H/D > AT > OLR > ST. The chosen parameters were all key impact factors as every calculated GERG was above 0.98. The optimal scopes of SGV, AT, OLR, ST, and H/D on SVI was 2.4–3.0 cm/sec, 169–227 min, 3–6 kg COD/(m^3·day), 2–3 min and 10–20. While, for set-up time, the optimal scopes turned out to be 2.4–3.4 cm/sec, 215–228 min, 3–6 kg COD/(m^3·day), 2–3 min and 16–20, respectively.

During aerobic granulation, the transformation of SVI and rapid set-up of the reactor were the result of the cooperation of multi-factors. Single or several factors could not improve the activated sludge's SVI and/or facilitate the set-up time alone. However, grasping the impact factor's influence degree and priority order could provide a deep understanding of the process of aerobic granulation. Additionally, in order to acquire granules with certain functions, the results generated could also serve as guidance to indicate the adjustment scope of each operational impact factor.

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References

Adav S S, Lee D J, Lai J Y, 2010. Potential cause of aerobic granular sludge breakdown at high organic loading rates. *Applied Microbiology and Biotechnology*, 85(5): 1601–1610.

Beun J J, Hendriks A, Van Loosdrecht M C M, Morgenroth E, Wilderer P A, Heijnen J J, 1999. Aerobic granulation in a sequencing batch reactor. *Water Research*, 33(10): 2283–2290.

Beun J J, Van Loosdrecht M C M, Heijnen J J, 2002. Aerobic granulation in a sequencing batch airlift reactor. *Water Research*, 36(3): 702–712.

Chang S H, Hwang J R, Doong J L, 2000. Optimization of the injection molding process of short glass fiber reinforced polycarbonate composites using grey relational analysis. *Journal of Materials Processing Technology*, 97(1-3): 186–193.

Chen Y, Jiang W J, Liang D T, Tay J H, 2008. Aerobic granulation under the combined hydraulic and loading selection pressures. *Bioresource Technology*, 99(16): 7444–7449.

Gao D, Liu L, Liang H, Wu W M, 2011. Comparison of four enhancement strategies for aerobic granulation in sequencing batch reactors. *Journal of Hazardous Materials*, 186(1): 320–327.

Guo F, Zhang S H, Yu X, Wei B, 2011. Variations of both bacterial community and extracellular polymers: The inducements of increase of cell hydrophobicity from biofloc to aerobic granule sludge. *Bioresource Technology*, 102(11): 6421–6428.

Hermansson M, 1999. The DLVO theory in microbial adhesion. *Colloids and Surfaces B: Biointerfaces*, 14(1-4): 105–119.

Hsiao S W, Tsai H C, 2004. Use of gray system theory in product-color planning. *Color Research and Application*, 29(3): 222–231.

Jiang H L, Tay J H, Tay S T L, 2002. Aggregation of immobilized activated sludge cells into aerobically grown microbial granules for the aerobic biodegradation of phenol. *Letters in Applied Microbiology*, 35(5): 439–445.

Kong Y H, Liu Y Q, Tay J H, Wong F S, Zhu J R, 2009. Aerobic granulation in sequencing batch reactors with different reactor height/diameter ratios. *Enzyme and Microbial Technology*, 45(5): 379–383.

Lee D J, Chen Y Y, Show K Y, Whiteley C G, Tay J H, 2010. Advances in aerobic granule formation and granule stability in the course of storage and reactor operation. *Biotechnology Advances*, 28(6): 919–934.

Li A J, Yang S F, Li X Y, Gu J D, 2008. Microbial population dynamics during aerobic sludge granulation at different organic loading rates. *Water Research*, 42(13): 3552–3560.

Li X M, Zeng G M, Wang M, Liu J J, 2003. Prediction of the amount of urban waste solids by applying a gray theoretical model. *Journal of Environmental Sciences*, 15(1): 43–46.

Li Z H, Kuba T, Kusuda T, 2006. The influence of starvation phase on the properties and the development of aerobic granules. *Enzyme and Microbial Technology*, 38(5): 670–674.

Liu L, Gao D W, Zhang M, Fu Y, 2010. Comparison of Ca_2^+ and Mg_2^+ enhancing aerobic granulation in SBR. *Journal of Hazardous Materials*, 181(1-3): 382–387.

Liu Y L, Gao S, Bai K, 2011. Research on the effect of hydraulic shear stress on the formation of aerobic granular sludge. In: International Symposium on Water Resource and Environmental Protection: 1308–1311.

Liu Y Q, Moy B Y P, Tay J H, 2007. COD removal and nitrification of low-strength domestic wastewater in aerobic granular sludge sequencing batch reactors. *Enzyme and Microbial Technology*, 42(1): 23–28.

Liu Y, Tay J H, 2004. State of the art of biogranulation technology for wastewater treatment. *Biotechnology Advances*, 22(7): 533–563.

Liu Y Q, Tay J H, 2008. Influence of starvation time on formation and stability of aerobic granules in sequencing batch reactors. *Bioresource Technology*, 99(5): 980–985.

Mosquera-Corral A, Arrojo B, Figueroa M, Campos J L, Méndez R, 2011. Aerobic granulation in a mechanical stirred SBR: treatment of low organic loads. *Water Science and Technology*, 64(1): 155–161.

Mosquera-Corral A, De Kreuk M K, Heijnen J J, Van Loosdrecht M C M, 2005. Effects of oxygen concentration on N-removal in an aerobic granular sludge reactor. *Water Research*, 39(12): 2676–2686.

Moy B Y P, Tay J H, Toh S K, Liu Y, Tay S T L, 2002. High organic loading influences the physical characteristics of aerobic sludge granules. *Letters in Applied Microbiology*, 34(6): 407–412.

Pai T Y, Hanaki K, Ho H H, Hsieh C M, 2007. Using grey system theory to evaluate transportation effects on air quality trends in Japan. *Transportation Research Part D: Transport and Environment*, 12(3): 158–166.

Peng Z, Kirk T B, 1999. Wear particle classification in a fuzzy grey system. *Wear*, 225-229(Part 2): 1238–1247.

Qin L, Liu Y, Tay J H, 2004. Effect of settling time on aerobic granulation in sequencing batch reactor. *Biochemical Engineering Journal*, 21(1): 47–52.

Tay J H, Liu Q S, Liu Y, 2001a. The effects of shear force on the formation, structure and metabolism of aerobic granules. *Applied Microbiology and Biotechnology*, 57(1-2): 227–233.

Tay J H, Liu Q S, Liu Y, 2001b. The role of cellular polysaccharides in the formation and stability of aerobic granules. *Letters in Applied Microbiology*, 33(3): 222–226.

Wan J F, Bessière Y, Spérandio M, 2009. Alternating anoxic feast/aerobic famine condition for improving granular sludge formation in sequencing batch airlift reactor at reduced aeration rate. *Water Research*, 43(20): 5097–108.

Wang S G, Gai L H, Zhao L J, Fan M H, Gong W X, Gao B Y et al., 2009. Aerobic granules for low-strength wastewater treatment: formation, structure, and microbial community. *Journal of Chemical Technology and Biotechnology*, 84(7): 1015–1020.

Wang Z W, Li Y, Liu Y, 2007. Mechanism of calcium accumulation in acetate-fed aerobic granule. *Applied Microbiology and Biotechnology*, 74(2): 467–473.

Zhang H M, Dong F, Jiang T, Wei Y, Wang T, Yang F L, 2011. Aerobic granulation with low strength wastewater at low aeration rate in A/O/A SBR reactor. *Enzyme and Microbial Technology*, 49(2): 215–222.

Zheng Y M, Yu H Q, Sheng G P, 2005. Physical and chemical characteristics of granular activated sludge from a sequencing batch airlift reactor. *Process Biochemistry*, 40(2): 645–650.

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