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Influence of magnetic field on activity of given anaerobic sludge

Y. B. Xu · X. J. Duan · J. N. Yan · Y. Y. Du · S. Y. Sun

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Abstract Two modes of magnetic fields were applied in the Cr^{6+} removal sludge reactors containing two predominated strains—*Bacillus* sp. and *Brevibacillus* sp., respectively. The magnetic field mode I* of 0–4.5 or 0–14 mT between pieces was obtained by setting the magnetic pieces with the surface magnetic density of 0–6 or 0–20 mT into the reactor, and the magnetic field mode II* of 6, 20, or 40 mT on the return line was obtained by controlling the working distance of the permanent magnet outside the sludge return line. The effects of different magnetic fields on the activity of the given anaerobic sludge were studied by comparing with the control (absent of magnetic field). The results showed that the magnetic field of 0–4 mT improved the activity of given sludge most effectively, $U_{max \cdot CH_4}$ (the peak methane-producing rate) and the methane producing volume per $gCOD_{Cr}$ reached 64.3 $mlCH_4/gVSS.d$ and 124 $mlCH_4/gCOD_{Cr}$, which increased by 20.6 and 70.7%, respectively, compared with the control. And the magnetic field of 20 mT took second place. It could be concluded that the input of some magnetic field could improve the activity of anaerobic sludge by increasing the transformation efficiency of COD_{Cr} matters to methane, and the total organic wastage did not increase.

Keywords Magnetic field · Sludge activity · Anaerobic sludge · Methane

Abbreviations

COD_{Cr}	Chemical oxygen demand
CH_4	Methane
MLSS	Mixed liquor suspended solids (mg/l)
(ML)VSS	Mixed liquor volatile suspended solids (mg/l)
SVI	Sludge volume index (ml/g)
SV_{30}	Sludge volume (%)
cfu	Colony forming unit

Introduction

As an effective method, magnetic separation technique had been applied to the treatment of many wastewaters, such as oil-bearing effluent, mine effluent (Karapinar 2003). Application of magnetic force to strengthen the suspended solid removal from wastewater, or combine application of magnetic particle with flocculent in emulsified mixture removal have been reported in some literatures, for example, the bio-functional magnetic beads, which were constituted by the powder

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Y. B. Xu (✉) · X. J. Duan · J. N. Yan · Y. Y. Du · S. Y. Sun
Faculty of Environmental Science and Engineering, Guangdong University of Technology, 510006 Guangzhou, China
e-mail: hopeybxu@tom.com

of *Rhizopus cohnii* and Fe_3O_4 particles coated with alginate and polyvinyl alcohol (PVA), could adsorb and recover Cr^{6+} from liquid, and the magnetic separation technology would make their separation more convenient (Li et al. 2008). Magnetic field applied in wastewater treatment systems could improve the degradation of organic matter by magnetizing wastewater and producing strong oxidant such as H_2O_2, which was a promising technique with low energy demand, easy operation, non-secondary pollution and low cost (Zhang 2002).

A great deal of researches showed that magnetized water had higher pH and electric conductivity than general tap water. In addition, magnetization can cause a higher osmotic pressure of water and stronger permeability through cell membrane (Boleslaw 1985; Lednev 1991). So a suitable magnetic field could promote microorganism abilities of nutriments absorption and utilization, and consequently accelerated their growth rate (Tu et al. 2004). Moreover, direct function of some magnetic field on intracellular water and substance could activate cytoenzyme and accelerate the bio-chemical reaction in creature bodies (Liboff et al. 2003). Fojt et al. studied biological effects of low-frequency electromagnetic fields ($t < 30$ min, $B_m = 10$ mT, $f = 50$ Hz) on three different bacterial strains—*Escherichia coli*, *Leclercia adecarboxylata*, and *Staphylococcus aureus.* The highest decrease of the viability (CFU) and the biggest magnetic field effect was observed with *E. coli.* The smallest magnetic field effect appears for *S. aureus* (Fojt et al. 2004). Afterwards, *P. denitrificans* was exposed to low-frequency magnetic field (10 mT, 50 Hz) for 24 min and denitrification activity of the cells decreased significantly by about 20% after magnetic field exposure. But *P. denitrificans* culture on electrode indicated 21% bacterial death after 24 min exposure of 10 mT magnetic field (Fojt et al. 2007). The magnetic fields (50 Hz, 10 mT) could kill a part of yeasts *Saccharomyces cerevisae* and the bigger part of them survived and continued in their growth (Novák et al. 2007). But a static and sinusoidal 50 Hz magnetic field (0.35 and 2.45 mT) did not induce alterations in the growth of *S. cerevisiae* (Ruiz-Gómez et al. 2004). And a magnetic field of 6 mT produced by a pair of permanent magnets could improve the growth of two Cr^{6+} bio-removal strains and increase the Cr^{6+} bio-removal rate (Xu and Sun 2008). These researches focused on some strains showed that just some magnetic field (some density and some mode) could be utilized for specific aim.

Few researches have been focused on the application of magnetic field to bio-system. Yavuz and Çelebi studied the effects of magnetic field on activity of activated sludge in a batch reactor system containing synthetic wastewater. The direct current (DC) magnetic field strength was changed in the ranges of 8.9–46.6 mT. The substrate removal rate was first increased by increasing the magnetic field strength, and reached the maximum at 17.8 mT, and decreased with further increase (Yavuz and Çelebi 2000). Tomska and Wolny investigated on the effect of magnetic field of induction 40 mT on organic compounds removal. And the results showed that COD_{Cr} removal for the testing unit where the activated sludge return was exposed to magnetic field was as higher as for the control unit. However, the analysis of nitrogen compounds transformations showed that elimination of organic nitrogen compounds was more effective for the unit with magnets by accelerating nitrification rate (Tomska and Wolny 2008). Chen and Li studied the effect of static magnetic field (42, 21, 7, 0 mT) on the production of polyhydroxyalkanoates (PHAs) from different short-chain fatty acids by activated sludge process under aerobic dynamic feeding (ADF) technique, It was demonstrated that the maximum poly-3-hydroxybutyrate (PHB) production occurring at 7 mT, and the minimum one at 42 mT; the maximum poly-3-hydroxyvalerate (PHV) production occurring at 21 mT, and the minimum one at 0 mT (Chen and Li 2008).

A survey of literature indicated that not much work had been done so far on magnetic field for wastewater bio-treatment and most of them had only focused on the treatment of the pollutants. However, the influence of magnetic field on the sludge activity is essential to drive the application of magnetic-biological combined technique in environmental protection, and this paper will report the influence for the first time. With previous researches, our team screened and obtained two strains A & B of high Cr^{6+} removal and reducing efficiency (Deng et al. 2004; Xu et al. 2005a, b; Xu and Sun 2005, 2008), and their growth rate reached the optimal at 6 mT in both solid and liquid medium. Tests on Cr^{6+}-contained wastewater also showed that the bio-system containing predominant strains with some magnetic field could removal Cr^{6+} more effective than the control. To avoid the fade away of magnetism, some methods should be taken to sustain a constant magnetic field. In this paper, the effects of different magnetic field modes and densities on the anaerobic sludge activity were compared and studied by the index of $U_{\max \cdot CH_4}$ (the peak methane-producing rate) and $U_{\max \cdot COD_{Cr}}$ (the peak COD_{Cr} removal ratio) according to the document (Hu 2003). The related researches have not been reported.

Experiment materials

Strains and sludge for tests

Strains A (*Brevibacillus* sp.) and B (*Bacillus* sp.) are two high-efficiency Cr^{6+}-removal bacteria, which were screened in our previous researches (Deng et al. 2004; Xu et al. 2005a, b; Xu and Sun 2005, 2008) and some of their main morphologic characteristics are listed in Table 1. The anaerobic sludge used in the experiments below was obtained from a municipal sewage plant in Guangzhou, to which the enough predominated strains were inoculated and the content of each strain was more than 10^8 cfu/g wet sludge after culture.

Table 1 Colony configurations of these two predominated strains

	Color	Shape	Edge	Size	Location
A	Buff	Round	Slick	Needle	Surface
B	Buff	Erose	Lacelike	About 0.2 cm	Surface

Test devices

Our devices were two anaerobic serial batch reactors (ASBR) with the same specs—20 cm (length) × 20 cm (breadth) × 55 cm (high) (as Fig. 1). MLSS of both reactors was 3,000 mg/l, and the anaerobic sludge was stirred slowly in the reactors by mixture-returning at the flux of 83.3 ml/min. The magnetic powder was magnetized to form an average magnetic density of 6.0 mT and added into reactor B at a mass ratio of magnetic powder: MLSS = 1:1, meanwhile, two kinds of magnetic fields were put on, respectively, to avoid the fade away of magnetism and sustain an constant magnetic field, which were named mode I* and mode II* as introduced below. While as a control, there was no magnetic powder and magnetization device in reactor A. The characteristics of the anaerobic sludge were showed in Table 2.

The duration of each ASBR operation units, such as wastewater inflow, anaerobic reaction, sludge sedimentation, water discharge and system unused were 0.5, 10, 12, 0.5, 1 h, respectively.

Magnetic fields

The mode I* of the magnetic field was obtained by setting a pair of permanent magnets (20 mm × 10 mm) outside the sludge return line, and a 20 mm-long magnetization zone offered the line exterior three magnetic fields of 6, 20, and 40 mT by controlling the working distance of the permanent magnets pair.

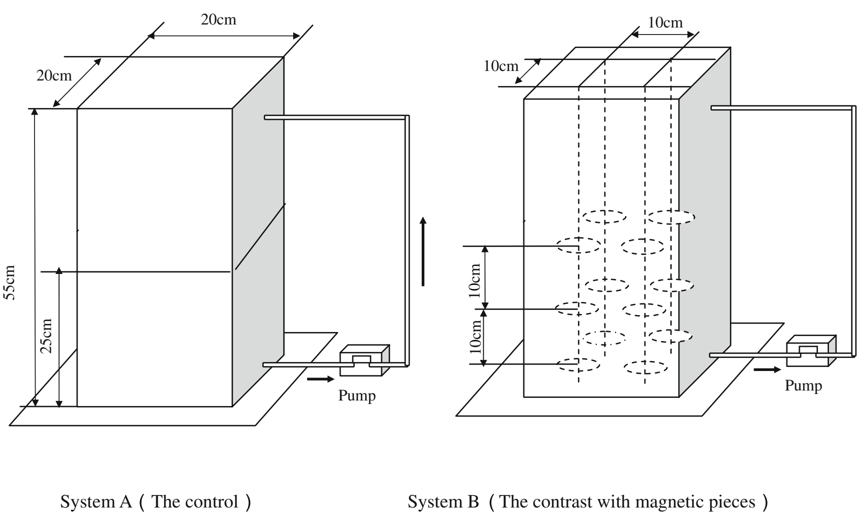

Fig. 1 Sketch maps of the test devices

Table 2 Characteristics of the activated sludge in the reactor A and B

Reactor		Index				
		SV_{30} (%)	SVI/(l g^{-1})	MLSS/(g l^{-1})	Ash constituent (%)	VSS/(g l^{-1})
A		38.0	33.3	11.4	41.5	6.80
B	I[a]	39.0	32.2	12.1	42.2	7.00
	II[b]	41.5	28.4	14.6	41.4	8.75

[a] Before the addition of magnetic powder

[b] After the addition of magnetic powder

The mode II* of the magnetic field was realized by setting magnetic pieces with the surface density of 0–6 or 0–20 mT into the reactor B. The introduce of two kinds of magnetic pieces provided magnetic fields of 0–4.5 and 0–14 mT between pieces, respectively. The distribution of the magnetic pieces was showed as Fig. 1.

So both kinds of the applied magnetic fields were inhomogeneous.

Wastewater and nutrient liquid

Synthetic wastewater contains some nutrients and supplements, such as glucose, KH_2PO_4, urea and trace metals. The water qualities are about COD_{Cr} of 180 mg/l and pH value of 6.6. The concentration of nutriment N and P was controlled according to the ratio of 200: 6: 1 (COD_{Cr}: N: P). This kind of wastewater was used as the inflow water of the reactor A and B.

Nutrient liquid made of CH_3COONa is about COD_{Cr} of 5,000 mg/l and pH value of 6.9, which is used in the determination of the anaerobic sludge activity.

Magnetic powder

The Fe_3O_4 powder was purchased from GuangZhou Magnetic Material Factory.

Methods

Determination of COD_{Cr} value and magnetic density

COD_{Cr} value of the wastewater was determined by COD_{Cr} quick mensuration.

The magnetic density was determined by platform tesla-meter PF-035-2 (produced by Litian Magneto-electrican Science and Technology LTD).

Determination of the anaerobic sludge activity

The anaerobic sludge activity can be reflected by two indexes: the peak methane-producing rate ($U_{\max \cdot CH_4}$) or peak COD_{Cr} removal ratio ($U_{\max \cdot COD_{Cr}}$) (Hu 2003).

$$U_{\max \cdot CH_4} = \frac{24KT_0}{XV_rT_1} \tag{1}$$

In which:K, the slope of the linear part in the accumulative methane output-time curve (ml CH_4/h); T_0, standard absolute temperature (273 K); T_1, absolute room temperature (K); X, sludge content (g/l); V_r, reaction zone volume of the batch reactor (L)

$$U_{\max \cdot COD_{Cr}} = \frac{U_{\max \cdot CH_4}}{Y_g}, \quad Y_g = \frac{V_{CH_4}(t)}{(S_0 - S)V_t} \cdot \frac{T_0}{T_1} \tag{2}$$

In which:Y_g, the transformation efficiency of COD_{Cr} matters to methane (ml CH_4/gCOD_{Cr}); $V_{CH_4}(t)$, the accumulative methane output by the end of the batch culture (ml); S_0, COD_{Cr} value of water sample in bottles at the beginning of culture (g/l); S, COD_{Cr} value of water sample in bottles by the end of culture (g/l)

When the magnetic field mode and density changed, the anaerobic sludge was sampled when the reactor B had been running steadily for 7 days, and then cultured with some nutrient liquid in a seal triangle bottle of 100 ml at 35 ± 1°C. The exhaust acid gas such as H_2S,CO_2 was absorbed by NaCl saturated solution including 2 N NaOH in 20 ml Shi fermentation tube, which was connected with the triangle bottle of 100 ml by a section of rubber tubes, and the measured gas was considered as the methane gas completely. Note down the accumulative output of methane (V_{CH_4}) each hour during the first 10 h and draw out a V_{CH_4}-t curve, k could be obtained by linear regression, which was the slope of the linear part in the accumulative methane output-time curve and the values of VSS in the bottles were also determined. To reduce the student error, ten groups of datum were averaged and used in calculation and plotting after a continuously 5 day-long running for each magnetic density.

Results and discussion

The influence of magnetic field mode I* on anaerobic sludge activity

The anaerobic sludge activity at 6 mT

When the magnetic density on the outer-surface of the sludge return line was 6 mT, the accumulative methane output of reactor A was higher than that of reactor B slightly (seen Fig. 2). Two equations were obtained by linear regression on the linear part in the accumulative methane output-time curves, that is $y_A = 1.736x \pm 0.689, y_B = 1.721x \pm 0.033$, so k_A and k_B were 1.736 and 1.721, respectively. The methane outputs per $gCOD_{Cr}$ (Y_g), the peak methane-producing rate ($U_{max \cdot CH_4}$) and the peak COD_{Cr} removal ratio ($U_{max \cdot COD_{Cr}}$) of reactor A and B were

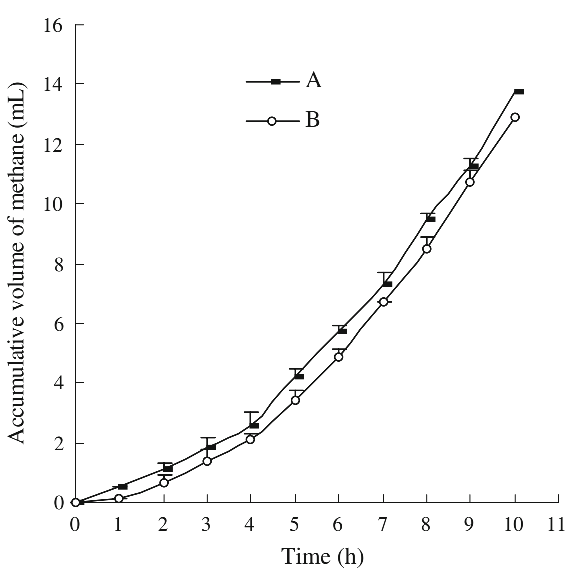

Fig. 2 Variation of the accumulated methane volume with the reaction time at 6 mT

Table 3 Results of the activated sludge in the reactor A and B at 6 mT

Index	Reactor	
	A	B
S_0 (g/l)	4,415.150	4,402.642
S (g/l)	3,609.666	4,057.435
K	1.736	1.721
X (g/l)	6.92	6.48
Y_g ($mlCH_4/gCOD_{Cr}$)	151	331
$U_{max \cdot COD_{Cr}}$ ($gCOD_{Cr}$/gMLVSS•d)	0.353	0.171
$U_{max \cdot CH_4}$ ($mlCH_4$/gMLVSS•d)	53.4	56.6

figured out and listed in Table 3, which showed that, compared with the control, Y_g and $U_{max \cdot CH_4}$ of sludge at 6.0 mT increased by 119 and 5.99%, respectively, but $U_{max \cdot COD_{Cr}}$ decreased by 51.6%. It was obvious that the magnetic field of 6 mT had a little influence on the sludge $U_{max \cdot CH_4}$, while the sludge consumed less COD_{Cr} matters.

The anaerobic sludge activity at 20 mT

When the magnetic density on the outer-surface of the sludge return line was 20 mT, the accumulative methane output of reactor B was higher than that of reactor A slightly (seen Fig. 3). Two equations were obtained by linear regression on the linear part in the accumulative methane output-time curves, that is $y_A = 1.537x \pm 1.250, y_B = 1.672x \pm 2.942$, so k_A and k_B were 1.537 and 1.672, respectively. The Y_g, $U_{max \cdot CH_4}$ and $U_{max \cdot COD_{Cr}}$ of reactor A and B were figured out and listed in Table 4, which showed that, compared with the control, Y_g and $U_{max \cdot CH_4}$ of sludge at 20 mT increased by 202 and 7.9%, respectively, but $U_{max \cdot COD_{Cr}}$ decreased by 64.3%. It was obvious that the magnetic field of 20 mT promoted the sludge $U_{max \cdot CH_4}$ visibly, while the sludge consumed less COD_{Cr} matters. So the magnetic powder-predominance strains system could produce much more methane by utilizing a unitage of COD_{Cr} matters at 20 mT than the control.

The anaerobic sludge activity at 40 mT

When the magnetic density on the outer-surface of the sludge return line was 40 mT, the accumulative methane output of reactor B was higher than that of

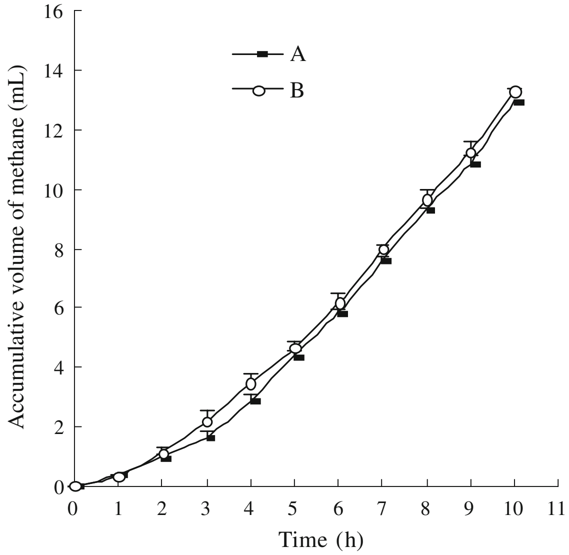

Fig. 3 Variation of the accumulated methane volume with the reaction time at 20 mT

Table 4 Results of the activated sludge in the reactor A and B at 20 mT

Index	Reactor	
	A	B
S_0 (g/l)	4,492.696	4,339.271
S (g/l)	3,695.551	4,069.109
K	1.537	1.672
X (g/l)	5.87	5.92
Y_g (mlCH$_4$/gCOD$_{Cr}$)	144	437
$U_{max \cdot COD_{Cr}}$ (gCOD$_{Cr}$/gMLVSS•d)	0.387	0.138
$U_{max \cdot CH_4}$ (mlCH$_4$/gMLVSS•d)	55.7	60.1

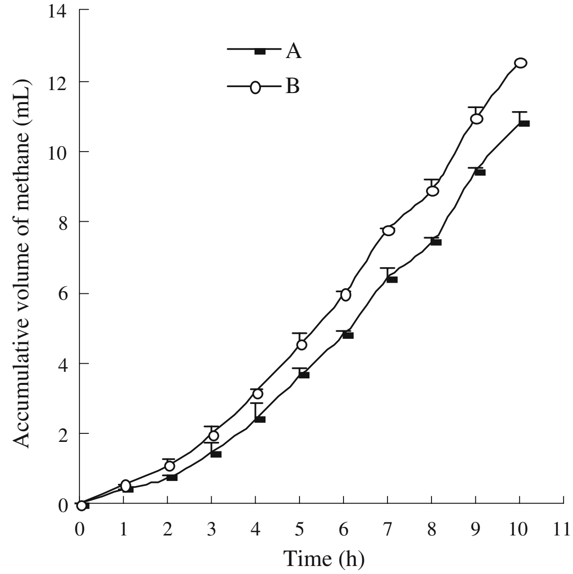

Fig. 4 Variation of the accumulated methane volume with the reaction time at 40 mT

Table 5 Results of the activated sludge in the reactor A and B at 40 mT

Index	Reactor	
	A	B
S_0 (g/l)	4,052.432	4,192.516
S (g/l)	3,500.101	3,962.378
K	1.277	1.475
X (g/1)	5.22	5.36
Y_g (mlCH$_4$/gCOD$_{Cr}$)	174	483
$U_{max \cdot COD_{Cr}}$ (gCOD$_{Cr}$/gMLVSS•d)	0.300	0.121
$U_{max \cdot CH_4}$ (mlCH$_4$/gMLVSS•d)	52.0	58.6

reactor A (seen Fig. 4). Two equations were obtained by linear regression on the linear part in the accumulative methane output-time curves, that is $y_A = 1.277x \pm 1.123, y_B = 1.475x \pm 1.645$, so k_A and k_B were 1.277 and 1.475, respectively. Y_g, $U_{max \cdot CH_4}$ and $U_{max \cdot COD_{Cr}}$ of reactor A and B were figured out and listed in Table 5, which showed that, compared with the control, Y_g and $U_{max \cdot CH_4}$ of sludge at 40 mT increased by 178 and 12.7%, respectively, but $U_{max \cdot COD_{Cr}}$ decreased by 59.7%. It was obvious that the magnetic field of 40 mT accelerated the sludge $U_{max \cdot CH_4}$ remarkably, while the sludge consumed far less COD_{Cr} matters. So the magnetic powder-predominance strains system could produce more methane by utilizing a unitage of COD_{Cr} matters at 40 mT than the control.

The influence of magnetic field mode II* on anaerobic sludge activity

The anaerobic sludge activity at 0–4.5 mT

When the magnetic density between two pieces of magnetic plates ranged from 0 to 4.5 mT, the accumulative methane output of reactor B was obviously higher than that of reactor A (seen Fig. 5). Two equations were obtained by linear regression on the linear part in the accumulative methane output-time

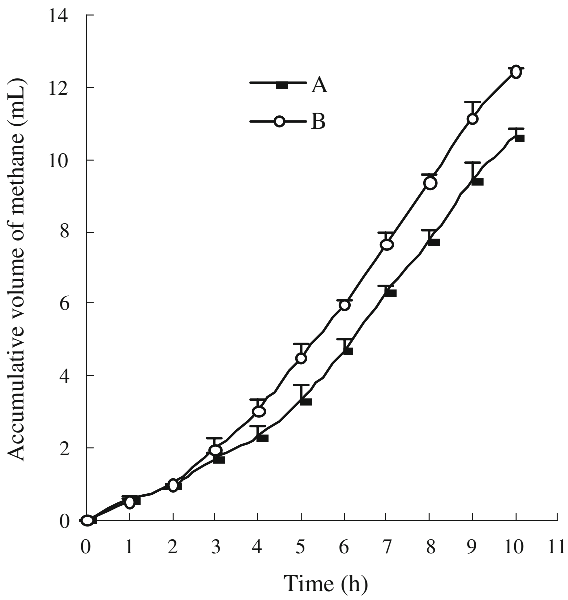

Fig. 5 Variation of the accumulated methane volume with the reaction time at 0–4.5 mT

Table 6 Results of the activated sludge in reactor A and B at 0–4.5 mT

Index	Reactor	
	A	B
S_0 (g/l)	4,570.743	4,237.543
S (g/l)	3,275.966	3,347.009
K	1.525	1.674
X (g/l)	6.09	5.54
Y_g ($mlCH_4/gCOD_{Cr}$)	72.8	124
$U_{max \cdot COD_{Cr}}$ ($gCOD_{Cr}$/gMLVSS•d)	0.732	0.518
$U_{max \cdot CH_4}$ ($mlCH_4$/gMLVSS•d)	53.3	64.3

curves, that is $y_A = 1.525x \pm 1.725, y_B = 1.673x \pm 2.714$,so k_A and k_B were 1.525 and 1.673, respectively. Y_g, $U_{max \cdot CH_4}$ and $U_{max \cdot COD_{Cr}}$ of reactor A and B were figured out and listed in Table 6, which showed that, compared with the control, Y_g and $U_{max \cdot CH_4}$ of sludge at 0–4.5 mT increased by 70.7 and 20.6%, respectively, but $U_{max \cdot COD_{Cr}}$ decreased by 29.2%. It was obvious that the magnetic field of 0–4.5 mT accelerated the sludge $U_{max \cdot CH_4}$ to the greatest extent, while the sludge consumed less COD_{Cr} matters. So the magnetic powder-predominance strains system could produce more methane by utilizing a unitage of COD_{Cr} matters at 0–4.5 mT than the control.

The anaerobic sludge activity at 0–14 mT

When the magnetic density between two pieces of magnetic plates ranged from 0 to 14 mT, the accumulative methane output of reactor B was higher than that of reactor A slightly (seen Fig. 6). Two equations were obtained by linear regression on the linear part in the accumulative methane output-time curves, that is $y_A = 1.853x \pm 2.678, y_B = 2.053x \pm 3.190$,so k_A and k_B were 1.853 and 2.053, respectively. Y_g, $U_{max \cdot CH_4}$ and $U_{max \cdot COD_{Cr}}$ of reactor A and B were figured out and listed in Table 7, which showed that, compared with the control, Y_g and $U_{max \cdot CH_4}$ of

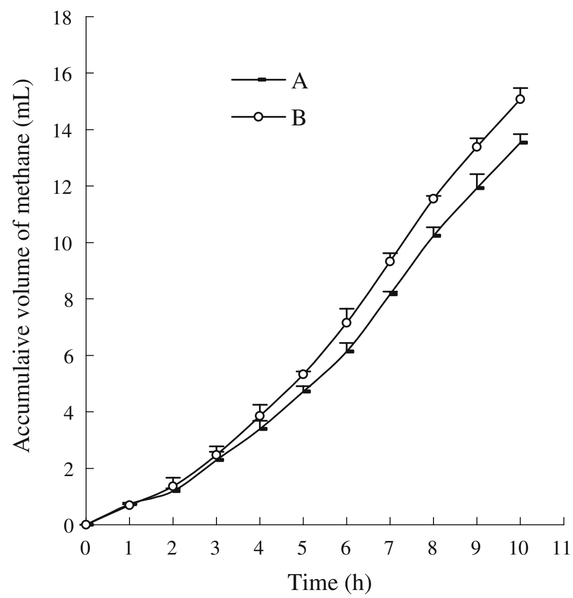

Fig. 6 Variation of the accumulated methane volume with the reaction time at 0–14 mT

Table 7 Results of the activated sludge in reactor A and B at 0–14 mT

Index	Reactor	
	A	B
S_0 (g/l)	3,902.342	3,940.365
S (g/l)	2,941.765	3,325.996
K	1.853	2.053
X (g/l)	5.80	5.52
Y_g ($mlCH_4/gCOD_{Cr}$)	125	218
$U_{max \cdot COD_{Cr}}$ ($gCOD_{Cr}$/gMLVSS•d)	0.544	0.364
$U_{max \cdot CH_4}$ ($mlCH_4$/gMLVSS•d)	67.9	79.1

sludge at 0–14 mT increased by 73.8 and 16.5%, respectively, but $U_{\max \cdot COD_{Cr}}$ decreased by 33.1%. It was obvious that the magnetic field of 0–14 mT accelerated the sludge $U_{\max \cdot CH_4}$ remarkably, while the sludge consumed less COD_{Cr} matters. So the magnetic powder-predominance strains system could also produce more methane by utilizing a unitage of COD_{Cr} matters at 0–14 mT than the control.

Conclusion

No matter the magnetic field mode I* of 6 , 20, and 40 mT or the magnetic field mode II* of 0–4.5 and 0–14 mT affected the activity of anaerobic sludge to some extend. All $U_{\max \cdot CH_4}$ values increased by 5.99–20.6%, moreover, the magnetic field produced by the magnetic pieces improved $U_{\max \cdot CH_4}$ more effective than that by the permanent magnets pairs outside the feedback pipe, and the sludge $U_{\max \cdot CH_4}$ with the magnetic field mode II* of 0–4.5 mT increased by 20.6%, which was the most remarkable one. While all $U_{\max \cdot COD_{Cr}}$ values decreased obviously by 29.2–64.3%, moreover, $U_{\max \cdot COD_{Cr}}$ of the sludge system with the magnetic field I* descended more distinct than that with the magnetic field II*, and the biggest $U_{\max \cdot COD_{Cr}}$ decrease of 64.3% could be obtained in the sludge system with the magnetic field I* of 20 mT. The results of methane output per $gCOD_{Cr}$ (Y_g) also showed that the methane yields based on COD_{Cr} of the sludge system with the magnetic field were higher than that of the control, which resembled $U_{\max \cdot CH_4}$. We found that the trends of $U_{\max \cdot CH_4}$ and $U_{\max \cdot COD_{Cr}}$ were inconsistent, which disagreed with the depiction of the direct ratio between $U_{\max \cdot CH_4}$ and $U_{\max \cdot COD_{Cr}}$ as demonstrated (Hu 2003). Combined the methane output per $gCOD_{Cr}$ and the sludge concentration variation in reactor A and B, it could be concluded that the introduction of some magnetic field improved the activity of the anaerobic sludge by increasing the transformation efficiency of COD_{Cr} matters to methane, and the total organic wastage didn't increase. Because the effects of magnetic fields on the anaerobic metabolic pathways, the degradation efficiencies and even the variation of the sludge concentrations during the system operation might be some reasons for the indirect ratio between $U_{\max \cdot CH_4}$ and $U_{\max \cdot COD_{Cr}}$, we chose the index of $U_{\max \cdot CH_4}$ as the activity of given anaerobic sludge in this research. Comparison between the effect of the magnetic field mode I* and that of the mode II* on the activity of given anaerobic sludge showed that even though the magnetic field mode II* could increase the sludge activity more effectively, the magnetic field mode I* could be added to existing bio-systems more simply.

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