脉冲上流式厌氧污泥床反应器的应用*

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摘要 将传统的连续式配水改为间歇式脉冲式配水，可改善反应器内的水力环境，促进基质与生物体之间的有效接触。脉冲配水使污泥的有机负荷COD达27.5 g/(L·d)，HRT降到约3 h，加速了污泥的颗粒化进程，47 d培养出良好的颗粒污泥。脉冲配水不会造成冲击负荷和中间产物积累，也不会造成大量污泥流失。在高负荷条件下，颗粒污泥中确实出现了大量的八叠甲烷球菌凝块。

关键词 厌氧消化，UASB反应器，脉冲配水，混合，污泥颗粒化，八叠甲烷球菌。

在UASB反应器的起动阶段，由于担心超负荷，一般采用低负荷，此时，进水量小，产气量也很少，反应器内缺乏搅动能力。UASB反应器在最大水力负荷1 $m^3/(m^2 \cdot h)$时，雷诺数只有1.6×10^{-11}，反应器内水流处于绝对层流状态，混合搅拌要完全依赖于所产生的气泡。一些微小气泡被吸附在污泥周围同污泥一起上浮(相当于气浮)，上浮污泥托住下沉污泥，形成高浓度的"塞子"，造成污泥脱节。因此，在起动阶段附加外力搅拌是必要的。在国外UASB反应器大都设有机械搅拌设备，但机械搅拌剪力太大，对颗粒污泥的形成极为不利。而本研究的脉冲配水提供了柔和的水力搅拌，促进污泥和污水之间的良好接触，使污泥上附着的气泡分离，有利"水力筛分"，提高反应器的负荷，加速污泥颗粒化进程。

1 试验中所用材料和方法

1.1 基质

在所有的废水中，啤酒废水最易培养出颗粒污泥。这大概由于啤酒废水含有麦芽糖、醇类以及酵酶。麦芽糖极易被分解成葡萄糖而被微生物所吸收，八叠甲烷球菌以甲醇为基质比以其它有机物为基质生长速度快[10]。因此，以太原天龙啤酒厂的啤酒废水为基质，其主要成分见表1。

表1 太原天龙啤酒厂废水成分分析结果(mg/L)

COD	1500—3000	Ca^{2+}	25.52—107.18	PO_4^{3-}	未检出
pH	6.5—7.0	Mg^{2+}	27.36—123.12	Co^{2+}	未检出
SS	100—300	Fe^{2+}	0.23—1.71	Ni^{2+}	未检出
NH_3-N	17.74—97.83	硫酸盐	185.42—834.39		

根据分析结果把进水COD：N：P调整到

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200 ∶ 5 ∶ 1。氮用尿素，磷用 KH_2PO_4 和 $(NH)_2HPO_4$(各占 1/2)。分别加入微量元素 Ni 0.1 mg/L；Co 0.05 mg/L；Mo 0.05 mg/L。

1.2 脉冲 UASB 反应器

脉冲 UASB 反应器用有机玻璃做成，截面方形，边长 0.15m，高 1.5 m，有效容积 28 L。脉冲发生器与反应器分开，容积 2 L。每次脉冲释放 0.5 L 进水，脉冲时间间隔 5—10 min，根据负荷和废水浓度调整。废水进入脉冲发生器，经预热后脉冲式地配入 UASB 反应器(见图 1)。

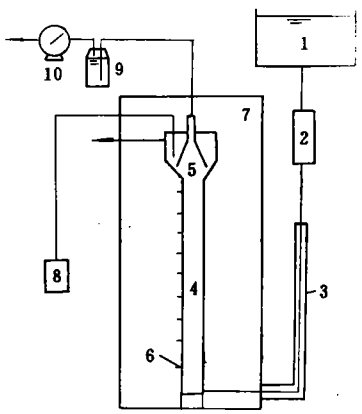

图 1　试验工艺流程

1. 高位水箱　2. 脉冲发生器　3. 预热毯
4. UASB 反应器　5. 三相分离器　6. 污泥取样口
7. 恒温箱　8. 温控仪　9. 水封　10. 湿式气表

1.3 主要运行参数

温度 35±1℃；pH7.0—7.5；进水 COD 浓度 1500—3000 mg/L；负荷根据 COD 去除率调整。

1.4 分析方法

COD、SS、NH_3-N、PO_4、VFAs 和硫酸盐根据美国公共卫生协会颁布的标准方法[1]。金属离子浓度用原子吸收分光光度计日立-1500 测试；电镜观察拍照用 JEOL-35C 电子显微镜，泥样在临界条件下干燥，分步脱水，再用 JEOL ion sputter JFC-1000 离子溅射仪喷金。污泥活性测试根据最大比产甲烷速率法[6]。

2 试验结果

2.1 接种污泥

因当地无消化污泥，以太原杨家堡污水厂的二沉池回流污泥为接种污泥。先以 200 目筛子过筛以去除砂子和大颗粒杂质，然后倒入一容器浓缩，浓缩 1 d 后，去除上清液。浓缩到第 2 d 污泥开始发酵，再无法去除上清液，便直接接种到反应器中。

2.2 反应器运行效果

在清水试验阶段，以 LiCl 为跟踪介质，对反应器中流态进行了测试。测试表明，脉冲配水能有效防止短流，去除死区，均匀配水。反应器运行到第 40 d 底部出现颗粒污泥。1 周后，污泥床全部变成颗粒污泥。颗粒污泥床占 1/3 反应器体积，此时反应器体积(包括膨胀床部分)负荷达 5 g/(L·d)。继续增加负荷，第 60 d 负荷达到 27.5 g/(L·d)，HRT 降到约 3 h。

2.3 颗粒污泥电镜照片

颗粒污泥直径 1.0—5.0 mm。电镜照片示于图 2。颗粒污泥表面凹凸不平，几处留有沼气从内部释放后所留下的孔洞(图 2A)。颗粒污泥内部存在相当大的自由空间(图 2C)，为气体和基质的交换提供了方便。在高负荷条件下，索氏甲烷菌(*Methanothrix*)在基质利用率、增长速度方面都不能与八叠甲烷球菌(*Methanoscarnia*)竞争，因而渐渐被淘态，颗粒污泥表面主要由八叠甲烷球菌组成(图 2D)。

2.4 负荷

UASB 反应器负荷要稳步增加，以 COD 去除率 85%作为界限，当 COD 去除率＞85%时，便可增加负荷。负荷增加幅度以现有负荷的 1/10 为宜。冲击负荷对颗粒污泥极为有害。当进水以现有负荷的 2.8/10 增加到反应器中时，结果使部分颗粒污泥漂浮到三相分离器液面上，膨胀床还出现了白色絮凝体。随后 4 d 减少负荷，两者均渐渐消失。

2.5 碱度

保持产酸菌与甲烷菌的绝对平衡是不可能的。这就要求混合液有一定缓冲能力，当有机酸有少量积累时，pH 不会波动。污泥在未颗粒化之前，对 pH 极为敏感。当 pH 低于 7.0 时，产气便不活跃。当把 pH 调整到 7.0 以上时，产气明显增加。由此可见，UASB 反应器最好保

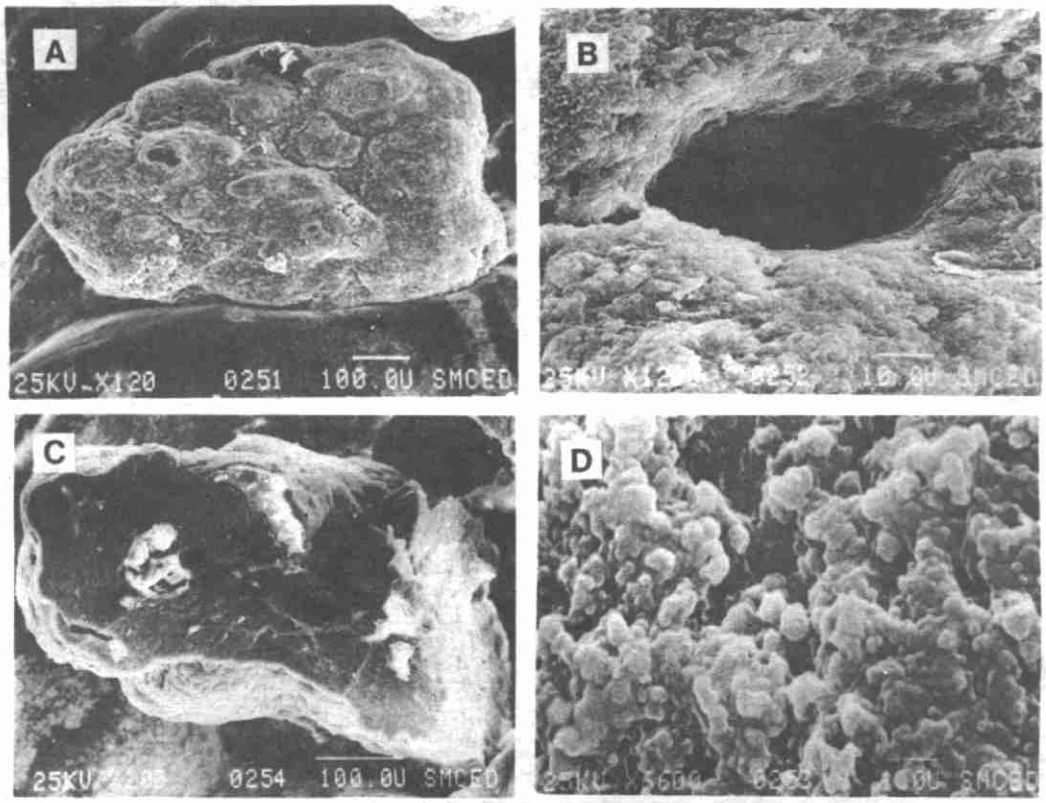

图2 颗粒污电镜照片

A. 颗粒污泥表面凹凸不平，几处留有沼气释放后留下的孔洞 B. 其中1个孔洞

C. 颗粒污泥截面 D. 颗粒污泥表面富集的八叠甲烷球菌

持在微碱性环境中(即 pH7.0—7.5；碱度＞2000 mg/L 以 $CaCO_3$ 计)。

3 讨论

细菌表面带有负电，似乎投加任何阳离子都有利于细菌的凝聚。但 Lettinga[4]建议投加 Ca^{2+}，它能促进污泥颗粒化进程。投加 Ca^{2+} 是基于下述原因：① Ca^{2+} 能稳定细胞外分泌出的多糖体(glycocalyx)，形成藻蛋白酸盐凝胶，粘结各种生物体，同时还作为细胞表面之间的连结体[7]；② Ca^{2+} 能将厌氧分解所产生的 CO_2 生成 $CaCO_3$ 晶体(几乎所有颗粒污泥都含有)，从而增加颗粒污泥的比重，改善颗粒污泥的沉降性能。本试验中，先用 $Ca(OH)_2$ 把硬度提高到13(德国度)，再用 $NaHCO_3$ 把 pH 调整到 7.0。因为碱度能提高反应器内的缓冲能力，防止 pH 波动。

在清水试验阶段，除对三相分离器集气效果、流量和温度进行测定外，还以 LiCl 为跟踪媒介，对反应器内的流态，配水均匀程度进行了测定。表明脉冲配水能有效防止短流，去除死区，使水力停留时间趋于一致。

目前分离出的产甲烷菌不下15种[3]。其中只有2种：索氏甲烷菌和八叠甲烷球菌能代谢乙酸[3]。研究还表明72%的甲烷是通过乙酸转化的[5]。若基质是溶解性的，甲烷转化是限速步骤，可见乙酸向甲烷转化在厌氧反应中举足轻重。电镜观察表明：颗粒污泥主要由乙酸代谢甲烷菌组成。索氏甲烷菌是只以乙酸为基质的丝状菌[3]，所生成的颗粒污泥比较松散，沉降性能差。八叠甲烷球菌是厌氧消化的优良菌种，具有形成的颗粒污泥紧密、比重大和沉降性能

好[3]以及对基质要求灵活，在氢压高时(>10^{-4} Pa)能还原 CO_2 的优点。

即：$CO_2+4H_2\rightarrow CH_4+2H_2O$

在氢压低时(<10^{-4} Pa)，代谢乙酸，

即：$CH_3COOH\rightarrow CH_4+CO_2$

特别是在氢压高时，能从反应器中不断去除 H_2，使酸化发酵产生的长链有机酸不断转化成乙酸[2]。

八叠甲烷球菌所产生的溶菌体(Lysis)可作为索氏甲烷菌的碳源，在内源呼吸期促进细菌凝聚[7]；其细胞壁由多糖组成，易与同细菌分泌出的多糖体以及其它细菌粘结，形成颗粒污泥[7]；生长速度快，是索氏菌的 4 倍[2]；对基质的代谢能力强，当乙酸浓度>300 mg/L 时，对基质利用速率是索氏甲烷菌的 3 倍[2]。

八叠甲烷球菌比表面小，对基质的亲合力差，即半饱和常数 K_S 大；而索氏菌是丝状菌，比表面大，对基质的亲合能力强，即半饱和常数 K_S 小，见图 3。

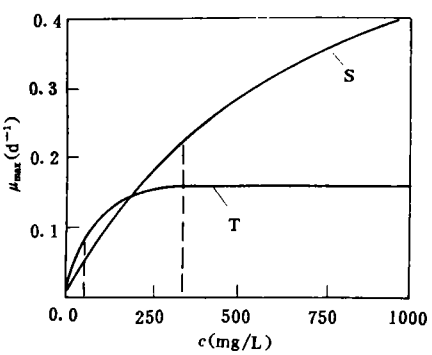

图 3　八叠甲烷球菌和索氏甲烷菌在不同乙酸浓度中的最大增长速率比较

S. 八叠甲烷球菌 $\mu_{max}=0.45\ d^{-1}$　$K_S=45$ mg/L

T. 索氏甲烷菌 $\mu_{max}=0.1\ d^{-1}$　$K_S=350$ mg/L

图 3 表明，高负荷时有利于八叠甲烷球菌生长繁殖；低负荷时有利于索氏甲烷菌的生长繁殖，当负荷(COD/VSS)超过 0.6 kg/(kg·d)时，颗粒污泥迅速形成[9]。试验中以 COD 去除率作为控制指标，当 COD 去除率超过 85%时，认为没有中间产物积累，即可增加负荷。

在试验中还以最大比产甲烷速率法[8]对不同时期乙酸代谢甲烷菌的活性进行了测定。结果表明，颗粒污泥活性是接种污泥的 15 倍。

4　结论

上流式厌氧污泥床反应器的间歇式脉冲配水系统较传统的连续式配水系统优越。脉冲配水迅速，均匀，没有死区，并能提供柔和的水力搅拌，促进生物体与基质之间的有效接触，提高了反应器的有机负荷，缩短了污泥颗粒化过程。八叠甲烷球菌是污泥颗粒化中的优良菌种。

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protection. In addition, the environmental drag were used to explain the model's meaning as well as to discuss the measurement of the environmental drag.

Key words: social rate of return, private rate of return, elasticity of elasticity, environmental discount rate, environmental investment, environmenal improvement, environmental drag.

The Growth and Purification Function of *Eichhornia crassipes* Solms in Oil-refinery Wastewater. Tang Shuyu et al. (Institute of Botany, Jiangsu Province and Chinese Academy of Sciences, Nanjing 210014): *Chin. J. Environ. Sci.*, **17**(1), 1996, pp. 44—46

The growth of *Eichhornia crassipes* Solms in oil-refinery wastewater has been described in this paper. An influence of COD, a comprehensive index of the pollultant concentration in the wastewater, on the growth of *Eichhornia crassipes* Solms was quantitatively studied. It was found that an optimum working condition for treating oil-refinery wastewater by *Eichhornia crassipes* Solms eco-engineering is established as follows: 65 mg/L<[COD]<131 mg/L; and 262. 6 mg/L of COD at effective critical point.

Key words: *Eichhornia crassipes*, oil-refinery wastewater, purification.

Study on Method of Sister Chromatid Exchange in *Vicia faba* to Detect Environment Mutagen. Kong Zhiming et al. (Dept. of Environ. Sci. and Eng., Nanjing University, Nanjing 210093): *Chin. J. Environ. Sci.*, **17**(1), 1996, pp. 47—49

The experimental conditions of the Brdu-Feulgen method of SCE in *Vicia faba* root which include the content of Brdu, labelling time of Brdu, the impacts on SCE of the content of hydrochloric acid and time and temperatrue for hydrolysis were studied and discussed in this paper. The best experiment conditions and procedure, which overcome the short-comings of FPG method that is complicated in procedure and, hence, difficult to be popularized, were obtained. In addition, such method was compared with other genotoxicology method in order to probe into the possibility of utilizing such technology to detect environment mutagen.

Key words: *Vicia faba*, SCE, Brdu-Feulgen method.

A Pulse-feed Upflow Anaerobic Sludge Blanket Reactor. Su Yumin et al. (Dep. of Environ. Eng., Taiyuan Univeristy of Technology, Taiyuan 030024): *Chin. J. Environ. Sci.*, **17**(1), 1996, pp. 50—53

The key parts of Upflow Anaerobic Sludge Blanket Ractor are gas-solids separator and feed system. The goals of this research, in which a conventional continuous feed system was replaced by an intermittent pulse-feed one, are to provide gently hydraulic mixing, to promote hydraulic selection, and to improve the contact between substrate and microorganisms. Pulse-feed method can raise the orgainc load rate as high as 27. 5 gCOD/(L. d), reduce HRT to nearly 3 hrs, and quickly develop granulated sludge in 47 days. It can not cause shock load and intermediates accumulation, as every pulse only releases a small amount of wastewater (1/56 reactor volume), which can not raise the substrate concentration in whole reactor. The pulse-feed also can not cause sever wash-out of sludge, because pulse-feed mi-xing can effectively separate sludge flocs and entrapped gas bubbles, and hence improve sludge settleability. The advantages of enrichment of *methanosarcina* species in the process of granulation are also discussed. At high load rate, *methanosarcina* species do appear in clumps on the granules.

Key words: anaerobic digestion, UASB, pulse-feed, mixing, granulation, *methanosarcina* species.

Study on Biological Pretreatment Method-bio-ceramic Reactor Treating Micro-pollution Source Water at Low Temperature and Low Turbidity. Hu Jiangyong et al. (Dept. of Environ. Eng., Tsinghua Univ., Beijing 100084): *Chin. J. Environ. Sci.*, **17**(1), 1996, pp. 54—56

One of biological pretreatment methods-bio-ceramic reactor (BCR) was used to treat a typical source water with micro-pollution at low temperature and low turbidity. By means of in-situ experiments with the bio-ceramic reactor, it was found that: the organic matter (OC or COD), ammonia, SS in the source water could be removed about 20%—30%, 60%—70% and 80%, respectively. Removl efficiency could be reduced at low temperature. Low turbidity and high concentration of organics in the source water would be benifical to BCR. In general, BCR would be a powerful way to purificate this kind of source water.

Key words: micro-pollution, source water, low temperature, low turbidity, organics, bio-ceramic pretreatment process.

Studies on the Leaching and Species of Aluminum in Soil. Huang Yanchu and Qu Changling (Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085): *Chin. J. Environ. Sci.*, **17**(1), 1996, pp. 57—59

The leaching and chemical forms of aluminum in soil by sequential fraction procedure were studied. Solutions used sequentially to extract Al are inorder of 1 mol/L KCl, 1 mol/L NH_4Ac, 1 mol/L HCl and 0. 5 mol/L NaOH. The spectrophotometric determination of leaching Al was performed with Eriochrom Cyamine RC. It has been found that the type of soil and the amounts of organic materials and total Al in soil have a siginificant effect on the amount of leaching Al. A certain amount of exchangeable Al can be leached from acid soil with 1 mol/L KCl extractant, however, it can not be leached from alkaline soil. The leaching Al extracted with 0. 5 mol/L NaOH is correlated at a high level of siginficance with the total Al in soil.

Key words: soil, leaching aluminum, chemical form.

Efficiency of Fluidized Biofilm Method for Treating Phenolic Wastewater. Yin Jun et al. (Jilin Architechtural and Civil Eng. Institute, Changchun 130021): *Chin. J. Environ. Sci.*, **17**(1), 1996, pp. 60—62

A dynamic experiment was conducted to examine the efficiency of the fluidized biofilm method with home-made carrier for treating phenolic wastewater. The experimental results have shown that COD and phenol were removed on an average over 80% and 90%—100%, respectively, while COD volumetric loading is 4. 0 kg/(m^3·d), and the final concentrations of COD and phenol in the effluent can meet Chinese Standard of Wastewater dischange permission. The biofilm can adhere quickly to the home-made carrier and the thickness of biofilm is suitable