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SBBR技术特性和动力学机制及其在废水处理中的应用

作　者：胡龙兴
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上学位论文

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The Characteristics and Kinetics of SBBR Technology and its Application in Wastewater Treatment

Candidate: Hu Longxing
Major: Fluid Mechanics
Supervisor: Prof. Liu Yulu

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答辩委员会对论文的评语

序批式生物膜反应器（SBBR）技术是当今新型的废水生物处理技术之一。作者广泛阅读了国内外文献并进行了充分的调研，选择 SBBR 技术特性和动力学机制及其在废水处理中的应用研究作为博士论文的研究课题，选题具有前沿性，论文的理论研究对水处理技术的发展具有推动作用，其应用研究具有实用价值。论文的主要研究成果如下：

(1) 作者设计了一种 SBBR 系统，并对 SBBR 技术的特性和处理模拟城市污水、模拟植物制剂废水的效果、SBBR 中有机物降解和氨氮转化的动力学模型进行了研究。

(2) 应用流体力学基本原理，考察了反应器系统的结构特性、反应器中的氧传递特性、流态特性和水力剪切力的作用。

(3) 根据 SBBR 脱氮的途径及其及其 SND 发生的可能，进一步研究了其作用机理，表明了 SBBR 技术具有处理生物抑制性废水的良好性能。

(4) 证实了 SBBR 的完全混合间歇式反应器模式，提出了 SBBR 中底物降解的三种典型规律，建立了废水中有机物降解和氨氮转化的动力学模型。

论文工作技术路线合理，实验方法正确，工作量大，实验结果真实可信。论文将流体力学用于环境工程研究具有理论创新。表明作者具有坚实的专业基础理论，以及较强的实验分析技能。已具备独立从事科学研究的能力。

论文条理清晰，层次分明。论文答辩中阐述清晰，能正确回答答辩委员会提出的问题。

答辩委员会表决结果

经答辩委员会表决，全票同意通过胡龙兴同学的博士学位论文答辩，建议授予工学博士学位。

答辩委员会主席：胡寿根

2004 年 1 月 16 日

摘 要

论文首先综述了序批式生物膜反应器(SBBR)技术及其在废水处理中应用研究的现状和发展趋势. SBBR 技术是一种新型复合式生物膜反应器技术. 它将序批式的运行模式与生物膜法相结合，具有两者的优点. 论文主要是以一种特定的系统来研究 SBBR 技术特性和动力学机制及其在废水处理中的应用.

研究内容之一：SBBR 技术的特性. 它包括：反应器系统、反应器中氧传递系数和充氧性能参数、反应器中的流态、反应器同时进出水的体积置换率（换水率）和反应器中的水力剪切力等. 研究结果表明：SBBR 是一种序批式外循环固定床生物膜反应器. 借助于专门设计的自控箱，SBBR 可运行 10 余种工艺模式. 在实验条件下，反应器内水的循环周期仅为 2 分钟，处于高速循环流动的条件，保证了传质和混合的良好效果. 在给定的工况下，SBBR 的氧传递系数 K_{La} 在 39~103 (h^{-1})之间，系统的充氧能力在 8.0×10^{-3}~20.5×10^{-3} kgO_2/h 之间. 反应器固定床陶粒层具有多孔介质性. 在不曝气的条件下，水流流过陶粒填料层时的流态为渗流. 在给定条件下，渗透率 $K=3.0175\times10^{4}$ μm^2. 不同曝气量下填料层压差与流速的线性关系显著. 在该反应器结构和运行条件下，反应器中存在明显的水力剪切力，其值为 0.962 dyn/cm^2. 水力剪切力对生物膜具有显著的影响，导致稳态的生物膜结构、平衡的生物膜厚度和密度. 本 SBBR 在进（出）水期的水流流态是介于理想推流和完全混合流之间，并以推流为主. 当水流进入反应器和 SBBR 进入反应期后，很快就处于完全混合流态. 只要

适当控制进水水力负荷，反应器的同时进出水体积置换率可达65%~74%. 可通过几条途径提高反应器的同时进出水体积置换率.

研究内容之二：SBBR技术处理模拟城市污水的可行性. 它包括：系统降解有机物(COD_{Cr})、硝化及反硝化的性能和效率. 具体包括：系统的启动，模拟城市污水中COD_{Cr}和NH_4^+-N去除的主要机理和影响因素，废水中总氮(T-N)去除程度及可能的脱氮途径，系统的氧利用效率，生物膜相的观察和分析. 实验结果表明：SBBR的挂膜和启动方式多样、速度快. 陶粒载体的挂膜属于表面吸附固定技术. 在挂膜过程中存在的水力剪切力是有益的. 生物膜对COD_{Cr}有明显的初期快速吸附作用. 系统对COD_{Cr}的去除非常有效，当COD_{Cr}容积负荷为1.38~6.32 kg/m^3·d，COD_{Cr}的去除率在90%以上. 在实验条件下，进水COD_{Cr}浓度对COD_{Cr}的去除率影响很小，COD_{Cr}的去除率都高达90%以上，出水COD_{Cr}均不超过100 mg/L，表明出水水质具有相当的稳定性，系统具有较强的抗冲击负荷能力. 当HRT少于75 min时，COD_{Cr}的去除率随HRT的增加而增加，当HRT大于75 min时，COD_{Cr}的去除率基本达到极限. 控制气水比在10:1左右使反应器中的DO保持在4~5 mg/L，对于O段反应模式是合适的. 在实验条件下，不同的COD/N对COD_{cr}的去除率几乎无影响，尽管柠檬酸钠的生物可降解性比蔗糖差，但在SBBR中用柠檬酸钠为碳源部分或全部替换废水中的蔗糖并未引起明显的差异. 当NH_4^+-N容积负荷在0.15~0.30 kg/m^3·d，相应的COD_{Cr}容积负荷为1.38~3.22 kg/m^3·d时，NH_4^+-N的去除率为61.5%~87.0%，T-N的去除率为55.0%~60.7%. 随着进水NH_4^+-N浓度上升（相应地COD_{Cr}容积负荷从1.4上升到6.3 kg/m^3·d），NH_4^+-N和T-N的去

除率下降. 对于固定的进水 NH_4^+-N 和 COD_{Cr} 浓度，随着 HRT 的延长，NH_4^+-N 和 T-N 的去除率都相应提高. 随着 COD/N 的增加，NH_4^+-N 和 T-N 的去除率相应增加，当 COD/N 为 31.4∶1.0 时，NH_4^+-N 和 T-N 的去除率达到 90%以上. 不同碳源对氮去除率的影响不大. 在 F(D)-O 模式下，在反应期处理水 pH 不断上升，使呈酸性的废水变成中性或弱碱性，这是有益的. 本 SBBR 在处理不同碳源、不同浓度的进水时，出水 SS 都较低，这与 SBBR 中以陶粒为填料有关. 在 SBBR 运行模式下，不同的工况导致不同的污泥产率. 在两种工况下求得的污泥产率分别为 0.12 kg VSS / kg COD 和 0.21 kg VSS/kg COD. 负荷越高，污泥产率也越高. 在较高负荷处理系统中，N 去除率不高，在有限的总氮去除中，通过同化合成去除的氮量占总去除氮量的 90%以上，通过硝化反硝化途径去除的 N 量很有限. 随着负荷的降低，相当于 HRT 延长，N 去除率升高，在总氮去除中，有 80%的 N 通过硝化反硝化途径去除，通过同化合成而去除的 N 量降到 20%. 在适当的负荷或 HRT 条件下，尽管反应器处于不断曝气的好氧条件下，但却能发生 SND 现象，其机理可从几方面来分析. 生物相镜检表明：微生物相较丰富，生物膜的质量较好. 在一定的供气量下本反应器中氧的利用率为 23.7%.

研究内容之三：探讨用 SBBR 技术处理模拟植物制剂（大蒜和黄连）废水的工艺条件，进行生物相观察和分析. 实验结果表明：采用 SBBR 技术处理具有生物抑制性的大蒜模拟废水时，梯度驯化是一种生物系统平稳过渡和快速启动的有效方法. 对于纯大蒜模拟废水，随 O 段反应时间、HRT 的增加、COD_{Cr} 容积负荷的减小，COD_{Cr} 去除率增加. 在各 COD_{Cr} 容积负荷下，出水的 pH 有 0.4~1.4 pH 单位的增幅. 在 SBBR 运行模式下，纯大蒜

模拟废水和模拟城市污水具有十分相似的处理效果，这可归因于SBBR的特点. 纯大蒜模拟废水在F(D)-O的模式下，原水pH低于6.5，经过O段反应，上升到7.5~7.9. 采用F(D)（15 min）–A(45min)–O(135min)的运行模式处理模拟大蒜和黄连废水，反应器中DO的时空分布符合厌氧和好氧的溶解氧要求，能产生合适的厌氧环境. 对于具有一定生物抑制性和生物难降解性的模拟大蒜和黄连废水的处理仅靠好氧反应模式是不够的，而采用F(D)(15 min)–A(30 min)–O(135 min)的模式是有效的. SBBR经一定时间运行后，反冲洗是必要的，可采用气水混合的方式. 反冲洗周期的长短与水力负荷、有机负荷以及反冲洗强度和持续时间有关. 实验中， 反冲洗周期一般为48~96小时. 对处理模拟大蒜和黄连废水过程的A段和O段的生物相镜检结果表明A、B段的生物相都较丰富，特征较明显.

研究内容之四：分析SBBR在反应期的动力学特征，探讨用SBBR技术去除模拟城市污水中COD_{Cr}和NH_4^+-N的动力学，建立相应的动力学模型. 研究结果表明：SBBR属于完全混合间隙式反应器. 针对该特点，考虑底物的扩散和生物降解作用，通过质量衡算建立了底物降解符合一级反应规律、零级反应规律和Monod方程的动力学模型. 这些模型描述了在生物膜内不同深度处底物浓度随时间的变化. SBBR反应期良好的湍流条件可以消除生物膜外扩散对反应的影响. COD在生物膜内的降解符合一级反应动力学规律. 在实验研究的范围内，对于不同的COD_{Cr}浓度、不同的C/N和不同的碳源下的COD_{Cr}降解过程线都具有类似的形态. COD_{Cr}的降解过程可用模型$C=C_0\exp(-K_1t)(1-\mathrm{erf}\xi)$描述. 通过对实验数据的回归可求出模型参数$C_0$和$K_1$. NH_4^+-N在生物膜内的转化符合零级反应动力学规

律，可忽略氨氮氧化过程中产生的中间产物的抑制作用；在 NH_4^+-N 转化过程初期的 3~4 小时，NH_4^+-N 几乎以等速率去除. NO_2^--N 含量在反应过程中一直保持非常低的水平，没有积累. 在反应后期 NO_3^--N 含量有时有较明显的上升. 对于低 C/N 的废水，NH_4^+-N 转化呈直线规律，NO_3^--N 浓度随反应过程的进行而升高. 对于高 C/N 的废水，NH_4^+-N 转化初期呈直线规律，然后处于非常低的极限浓度，NO_3^--N 浓度随反应时间增加一直处于较低的水平. 在实验 C/N 下，在反应期 NO_2^--N 含量都处于非常低的水平，没有积累现象. NH_4^+-N 的转化过程可用模型 $C = C_0\left(1-\mathrm{erf}\xi\right)-K_0t$ 描述. 通过对实验数据的回归可求出模型参数 C_0 和 K_0.

关键词　废水处理，序批式生物膜反应器，生物膜法，动力学

Abstract

In this paper the state of the art is reviewed of Sequencing Batch Biofilm Reactor (SBBR) technology and its application in the wastewater treatment first. SBBR technology is a new type of combined biofilm reactor technology. It combines the sequencing batch operation mode with the biofilm process with both advantages.This research work focused on the study of the characteristics, kinetics and application in wastewater treatment of SBBR technology by means of a type of specific reactor systems.

The first part of the research work is on the characteristics of SBBR technology. It included SBBR reactor system, the oxygen transfer coefficients and oxygenating performance parameters, the fluid flow pattern in the reactor, the volumetric exchange rate of feeding and draining simultaneously in the reactor, and the hydrodynamic shear force in the reactor. The research results showed that the SBBR employed is a type of packed bed SBBR with external recirculation loop. The reactor system is capable of operating in more than ten modes by means of the automatic control box designed specially. Under the operation conditions, the water in the reactor is at the state of high speed recirculation resulting in the good mass transfer and mixing effects; Under the experimental conditions, the oxygen transfer coefficients K_{La} are between 39~103 (h^{-1}) and the oxygenating capacity is from 8.0×10^{-3} to 20.5×10^{-3}

kgO_2/h; The filling stuff composed of ceramic grains belongs to the porous media. Under the condition of no aeration, the flow pattern in the packed bed of the reactor is infiltration. Under the given conditions, the infiltration rate K equals 3.0175×10^4 μm^2; Under different aeration intensity the linear relationship between the pressure difference and flow speed in the packed bed was obvious. Under the operation conditions of the reactor there is the obvious hydrodynamic shear force which is typically equivalent to 0.962 dyn/cm^2. Hydrodynamic shear force has the marked influences on the biofilm leading to the steady state structure, the equilibrium thickness and density of biofilm. During the feeding (draining) phase of the reactor the flow pattern is between ideal plug flow and completely mixing flow and is mainly characterized by plug flow. During the reaction phase, the influent, after entering the reactor, rapidly became the completely mixing flow. The volumetric exchange rate of feeding and draining simultaneously in the reactor can reach 65%~74% if only the influent hydraulic loading rate is controlled properly. There are several ways to increase the volumetric exchange rate.

The second part of the research work is on the feasibility of treatment of simulated municipal wastewater with SBBR technology. It included the performance and efficiency of the removal of carbonaceous organic wastes (COD) and nitrification and denitrification. It can be further divided into the followings: the start-up of the system , the examination of principal mechanisms and influencing factors of the removal of COD and NH_4^+-N, the

examination of the degree and routes of the removal of total nitrogen (T-N) or NH_4^+-N, the estimation of oxygen utilization efficiency of the system and the microscopic examination and analysis of the phase of the microbial communities. The experimental results showed that there were several rapid ways to immobilize and acclimatize the microbial communities in SBBR. The immobilization of the microbial communities on the filling stuff of ceramic grains belonged to the surface adsorption immobilization process. The existence of hydrodynamic shear force during the microbial immobilization was favorable. The biofilm had the obvious initial rapid adsorption of COD. The SBBR was very effective to remove COD and the removal rates of COD reach more than 90% when the volumetric loading rate of COD was from 1.38 to 6.32 $kg/m^3 \cdot d$. Under the experimental conditions influent COD concentration had little effect on the COD removal rates of more than 90% and the effluent COD was always below 100 mg/L, which meant that the effluent quality was quite stable and the SBBR possessed stronger performance against the shock load. When the HRT was less than 75 min., the COD removal increased with the increased HRT and reached the upper limit when the HRT was more than 75 min. With respect to the aerobic reaction phase, it was appropriate to keep the DO in the reactor to be 4 to 5 mg/L by controlling the ratio of air to water of 10:1. Under the experimental conditions the different ratios of COD/N had little influence on the COD removal. Although the biodegradability of sodium citrate was inferior to that of sucrose, the partial and complete replacement of

sucrose with sodium citrate used as carbon source in the reactor did not bring about obvious difference. When the volumetric loading rate of NH_4^+-N was 0.15~0.30 kg/m^3·d，correspondingly, the volumetric loading rate of COD was 1.38~3.22 kg/m^3·d, the NH_4^+-N removal was 61.5%~87.0% and the T-N removal was 55.0%~60.7%. As the influent NH_4^+-N concentration increased (correspondingly, the volumetric loading rate of COD increased from 1.4 to 6.3 kg/m^3·d),the removal of NH_4^+-N and T-N decreased. With respect to the fixed NH_4^+-N and COD concentrations in the influent, the removal of NH_4^+-N and T-N correspondingly increased with the increased HRT. The removal rates of NH_4^+-N and T-N also increased with the ratio of COD/N. When the ratio of COD/N equaled 31.4：1.0, the removal of NH_4^+-N and T-N reached more than 90% respectively. The different types of carbon source had a little effect on the nitrogen removal. Under the operation mode of F(D)-O the pH of the treated water continuously increased during the reaction phase with the result that the pH of the water changed from acidity to neutrality or weak basicity, which was desirable. When the wastewaters of different carbon sources and different influent concentrations were treated, the SS in the effluent was under a low value, which is relevant to the ceramic grains used as filling stuff. Under SBBR operation mode different operation conditions resulted in the different sludge yields. The yields obtained under two operation conditions equaled 0.12kg VSS/kg COD and 0.21 kg VSS/kg COD respectively. The higher the loading, the higher the sludge yield. In the treatment system with higher loading rates the nitrogen removal was not high; in the limited T-N removal the nitrogen removal by assimilation accounted for more than 90% of the total nitrogen removal and that by nitrification and denitrification was very limited. With the decrease of the loading rate, corresponding to the increase of HRT, NH_4-N could be more thoroughly oxidized leading to the increased nitrogen removal. In this case, the nitrogen removal by nitrification and denitrification accounted for 80% of T-N removal and that by assimilation decreased to 20%. Under the appropriate conditions of loading rate or HRT there were the phenomena of simultaneous nitrification and denitrification (SND) although the reactor was under the aerobic condition. The possible mechanisms involved in the phenomena could be explained in several aspects. The microscopic examination of the microorganisms phase showed that there were various typical microbial communities corresponding to the exerted environmental condition and better biofilm quality. The utilization rate of oxygen under the given air supply in the reactor was 23.7%.

The third part of the research work is on the process of treating the simulated wastewater containing botanic products (garlic and golden thread) with SBBR technology and the microscopic examination and analysis of the microorganisms phase. The experimental results showed that when the simulated garlic wastewater biologically inhibitory was treated with SBBR technology, the gradient acclimation was an effective method for the stable transition and rapid start-up of the biological system. With the simulated single garlic wastewater COD removal increased with the