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有机物对厌氧氨氧化微生物燃料电池脱氮产电性能的 影响

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摘要:通过接种厌氧氨氧化污泥到微生物燃料电池阳极,成功启动厌氧氨氧化微生物燃料电池(ANAMMOX-MFC),研究了葡萄糖和苯酚对 ANAMMOX-MFC 脱氮产电性能的影响. 结果表明,当葡萄糖浓度较低时(100~200 mg·L $^{-1}$)时,对 ANAMMOX 菌有促进作用,ANAMMOX-MFC 脱氮产电性能增强,此时反应器进出水 COD 浓度变化不大;当葡萄糖浓度高于 300 mg·L $^{-1}$ 时,产电性能逐渐下降,NH $_4^+$ -N去除率和去除速率逐渐下降,而NO $_2^-$ -N去除率和去除速率基本保持不变,此时出水 COD 浓度也出现降低,说明厌氧氨氧化菌活性受到抑制,反硝化菌活性开始增强. 极化曲线拟合程度较低,COD 浓度变化对电池内阻影响较小. 当苯酚浓度较低时(50~100 mg·L $^{-1}$),对 ANAMMOX-MFC 脱氮产电性能影响较低;当苯酚浓度超过 200 mg·L $^{-1}$ 时,ANAMMOX-MFC 脱氮产电性能逐渐被抑制. 整个过程进出水 COD 浓度变化不大,极化曲线拟合程度较低,表观内阻有缓慢升高.

关键词: 厌氧氨氧化微生物燃料电池(ANAMMOX-MFC); 葡萄糖; 苯酚; 脱氮; 产电中图分类号: X703 文献标识码: A 文章编号: 0250-3301(2018)08-3937-09 **DOI**: 10.13227/j. hjkx. 201711104

Effects of Organic Substrates on ANAMMOX-MFC Denitrification Electrogenesis Performance

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Abstract: An anaerobic ammonium oxidation microbial fuel cell (ANAMMOX-MFC) was successfully started by inoculating anaerobic ammonium oxide sludge into the anode of a microbial fuel cell and then used to study the effect of glucose and phenol on ANAMMOX-MFC denitrification electrogenesis performance. The results showed that the ANAMMOX bacteria promoted ANAMMOX-MFC denitrification when the concentration of glucose was low (100-200 mg·L⁻¹). At that time, the chemical oxygen demand (COD) concentration of the reactor was not significant. The electrogenesis production performance and NH₄⁺-N removal rate gradually decreased when the glucose concentration was higher than 300 mg·L⁻¹, but the NO₂⁻-N removal rate generally remained unchanged. The COD concentration was also reduced, indicating that the activity of the ANAMMOX bacteria was inhibited and the activity of denitrification bacteria began to increase. The polarization curve fitting degree was low, and the change in COD concentration had little effect on the battery internal resistance. When the concentration of phenol was low (50-100 mg·L⁻¹), there was little effect on ANAMMOX-MFC denitrification electrogenesis performance. When the concentration of phenol exceeded 200 mg·L⁻¹, ANAMMOX-MFC denitrification performance was gradually inhibited. Overall, in the process, the COD concentrations of the water influent and effluent changed little, the polarization curve fitting degree was low, and the apparent internal resistance increased slowly.

Key words: anaerobic ammonium oxidation microbial fuel cell (ANAMMOX-MFC); glucose; phenol; denitrification; electrogenesis

微生物燃料电池(microbial fuel cell, MFC)是以细菌为催化剂,氧化有机物和无机物产生电流的装置.这些代谢反应产生的电子,通过外电路从阳极到阴极,从而产生了电流^[1]. MFC 具有很多吸引人的地方,如直接产电,能量转化效率高,能在室温下进行反应.特别地,MFC 在实现废水处理的同时能够减少污泥的产生^[2]. MFC 的研究主要集中在有机废水处理上^[2-4].人们采用 MFC 对食品工

业废水、酒工业废水、甜食工业废水、牛奶工业废水、农业加工废水、纸回收工业废水、城市生活污水等进行了研究^[5~7].近来,兼具脱氮功能的 MFC

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成为了研究的新焦点^[8,9]. Zhen 等^[10]构建了以氨 为唯一能源的 MFC, 推测硝化细菌能直接以氨为燃 料进行产电或通过化能自养代谢过程合成有机物为 其他异养产电菌提供能源. 谢作甫[11] 构建了氨氧 化微生物燃料电池(ammonia-oxidation microbial fuel cell, AO-MFC), 探明了溶解氧(DO)对硝化和产电 性能的影响及其机制. 张吉强[12]首次创建了阳极 反硝化微生物燃料电池(anodic denitrification MFC, AD-MFC),系统而深入地研究了 AD-MFC 的脱氮产 电性能. Virdis 等[13] 利用 A/O 工艺与 MFC 结合, 首先将氨和有机物通入阳极, 当有机物在阳极去除 完毕后, 将阳极液通入外置硝化反应器, 进行硝化 反应, 再将出水通入阴极进行反硝化反应, 最终转 化为氮气, 完成脱氮过程. Virdis 等[14] 对反硝化 MFC 进行了改进,省略了外置硝化反应器,直接对 阴极进行曝气, 实现了阴极同步自养硝化反硝化. Sotres 等[15] 在研究双室微生物燃料电池中, 通过对 阴极室间歇曝气实现了同时硝化反硝化菌群的建 立,并进行了微生物群落分析.

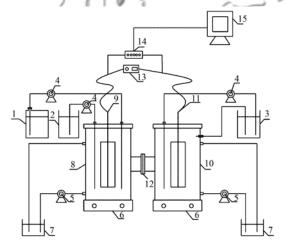
厌氧氧氧化 (anaerobic ammonium oxidation, ANAMMOX) 菌是新发现的一类脱氮细菌, 其能够 在厌氧条件下以氨为电子供体、亚硝酸盐为电子受 体产生氮气(NH₄ + NO₅ ===N₂ + 2 H₂O)^[16]. 以 该反应开发的 ANAMMOX 工艺是一种新兴的废水 生物脱氮工艺,可同时去除氨和亚销酸盐两种氮素 污染物[17]. 厌氧氨氧化微生物燃料电池可实现氨 氮和亚硝氮的同时去除,目前研究较少. 谢作 甫[11] 构建了厌氧氨氧化微生物燃料电池 (anaerobic ammonium oxidation MFC, ANAMMOX-MFC), 探明了其脱氮和产电性能, 结果表明: ANAMMOX-MFC 容积负荷和容积去除速率(以 N 计)分别为 1.72~2.57 kg·(m³·d)⁻¹和 1.64~ 2. 38 kg·(m³·d) -1, 氨氮和亚硝氮去除率分别为 88.9%~98.3%和88.7%~97.2%.张吉强[12]创 建了厌氧氨氧化微生物燃料电池(ANAMMOX-MFC),探明了其脱氮产电性能,考察了温度、pH 和中介体对 ANAMMOX-MFC 脱氮产电性能的影 响,但仍需进一步探明不同影响因素对厌氧氨氧 化微生物燃料电池脱氮产电性能的影响. 由于实 际废水中难免会存在有机物, 研究有机物对厌氧 氨氧化微生物燃料电池脱氮产电性能的影响变得 十分有意义.

本研究通过接种厌氧氨氧化污泥到微生物燃料 电池阳极,成功启动 ANAMMOX-MFC 达到稳定性 能的基础上,并进一步研究有机物对 ANAMMOX - MFC 的影响,旨在为此新工艺提供理论依据.

1 材料与方法

1.1 ANAMMOX-MFC 系统

本实验在张吉强[12]研究基础上构建了双室 ANAMMOX-MFC, 实验装置如图 1 所示. MFC 由有 机玻璃制成, 阴极室和阳极室由两个圆柱体构成, 圆柱体含中间保温层,双室有效容积均为550 mL (实际溶液体积 450 mL), 中间由圆形的质子交换 膜(Nafion 117)分隔开, 有效面积为 19.6 cm2. ANAMMOX-MFC 放置于可调节转速的磁力搅拌器 上,阳极和阴极均用石墨毡作电极(10 cm ×4 cm × 0.5 cm), 从而增大了接触面积. 石墨毡由钢丝固 定于容器中部悬空, 距底面 4 cm, 平行于质子交换 膜. 中空保温层由潜水泵将水浴锅中温水泵入保温 层, 保证反应器温度. MFC 阳极接进水桶和出水 桶,采用序批式进出水,由中控系统和蠕动泵控制 进出水. 阴极接进水桶和出水桶, 采用连续进出 水. 阴极室和阳极室外接可变电阻箱(0~9990 Ω) 调节电阻大小, 外联数据采集卡(USB-1408FS-PLUS), 并用电脑记录



1. 阳极室进水桶; 2. 阳极室出水桶; 3. 阴极室储液桶; 4. 蠕动泵; 5. 热水循环泵; 6. 磁力搅拌器; 7. 恒温水浴锅; 8. 阳极室; 9. 阳极; 10 阴极室; 11. 阴极; 12. 阳离子交换膜; 13. 可变电阻箱; 14. 数据采集卡; 15. 电脑

图 1 ANAMMOX-MFC 装置示意

Fig. 1 Schematic diagram of the ANAMMOX-MFC system

1.2 厌氧氨化污泥的接种

接种污泥为厌氧氨氧化污泥,取自实验室(重庆大学煤矿灾害动力学与控制国家重点实验室)内前期培养3个月并实现稳定运行的厌氧氨氧化反应器. 其中 SS 为 1596.5 mg·L⁻¹, VSS 1221.3

mg·L⁻¹, VSS/SS 为 0.765, 接种量为 450 mL.

1.3 模拟废水

阳极室进水为模拟废水,进水基质为

 $(NH_4)_2SO_4$ 、 $NaNO_2$,浓度按需要添加. 参考相关报道 [18],进水主要元素浓度如表 1 所示. 阳极进水 pH 控制在 7.5 左右.

表1 厌氧氨氧化模拟废水成分1)

Table 1 Simulation of anaerobic ammonium oxidation (ANAMMOX)

成分	NaHCO ₃	$\mathrm{KH_{2}PO_{4}}$	$MgSO_4 \cdot 7H_2O$	CaCl_2	$FeSO_4 \cdot 7H_2O$	EDTA	$(\mathrm{NH_4})_2\mathrm{SO_4}$	NaNO_2	微量元素 I	微量元素 Ⅱ
单位/mg·L-1	1 000	27. 2	200	300	6. 25	6. 25	ND	ND	1	1

1) 微量元素 I :EDTA 5 000 $mg \cdot L^{-1}$, $FeSO_4 \cdot 7H_2O$ 5 000 $mg \cdot L^{-1}$; 微量元素 II :EDTA 15 000 $mg \cdot L^{-1}$, $ZnSO_4 \cdot 7H_2O$ 430 $mg \cdot L^{-1}$, $CoCl_2$ 240 $mg \cdot L^{-1}$, $MnCl_2 \cdot 4H_2O$ 990 $mg \cdot L^{-1}$, $CuSO_4 \cdot 5H_2O$ 250 $mg \cdot L^{-1}$, $NaMoO_4 \cdot 2H_2O$ 220 $mg \cdot L^{-1}$, $NiCl \cdot 6H_2O$ 190 $mg \cdot L^{-1}$, $Na_2SeO_4 \cdot 10H_2O$ 210 $mg \cdot L^{-1}$, H_3BO_4 14 $mg \cdot L^{-1}$

1.4 实验方案

阳极室外接储液桶 20 L, 在配置进水之前采取通入氮气排氧, 并在储液桶一端接入氮气压缩袋, 尽量保持厌氧条件. 阳极室进水控制基质浓度 1:1, 控制NH₄⁺-N和NO₂⁻-N均为 90 mg·L⁻¹. 阴极室采用蠕动泵连续进水, 高锰酸钾 8 mmol·L⁻¹作为阴极电子受体. 采用小型潜水泵将恒温水浴锅中的水泵入反应器保温隔层, 将温度控制在35℃±1℃, 通过盐酸和碳酸氢钠调节 pH 维持在7.5 左右, 外接电阻为1 000 Ω. 系统采用锡箔纸覆盖微生物燃料电池反应器, 使之达到避光的条件. 通过中控系统设定水力停留时间(HRT)为 8 h(进水 5 min、厌氧反应 450 min、沉淀 20 min、排水 5 min).

1.4.1 葡萄糖对 ANAMMOX-MFC 性能的影响实验

本实验选用葡萄糖为研究对象,考察不同浓度葡萄糖对 ANAMMOX-MFC 脱氮产电性能的短期影响.设定不同的葡萄糖浓度梯度,分别为100、200、300、400 和 500 mg·L⁻¹.每一浓度梯度连续进行 2个周期实验,待稳定后通过改变电阻箱阻值9 000~20 Ω测定极化曲线,连续实验结束后恢复之前进水状态(不添加葡萄糖),待性能恢复后重复上述实验,待两次实验数据相差小于 5% 时提升进水葡萄糖浓度,进行下一浓度实验.

1.4.2 苯酚对 ANAMMOX-MFC 性能的影响实验

本实验选用苯酚为研究对象,考察不同浓度苯酚对 ANAMMOX-MFC 脱氮产电性能的短期影响.设定不同的苯酚浓度梯度,分别为 50、100、200、300、400 mg·L⁻¹.每一浓度梯度连续进行 2 个周期实验,待稳定后通过改变电阻箱阻值9 000 ~ 20Ω测定极化曲线,连续实验结束后恢复之前进水状态(不添加苯酚),待性能恢复后重复上述实验,待两次实验数据相差小于 5% 时提升进水苯酚浓度,进

行下一浓度实验.

1.5 实验检测指标与方法

(1)化学指标

采用重铬酸钾法测化学需氧量(COD);纳氏试剂光度法测氨氮(NH₄⁺-N); N-(1-萘基)-乙二胺光度法测亚硝态氮(NO₂⁻-N); 酚二磺酸光度法测硝态氮(NO₃⁻-N); 玻璃电极法测 pH 值; 水银温度计测温度.

(2) 电化学指标

ANAMMOX-MFC 的输出电压 U(mV) 通过数据 采集卡每隔 30 s 自动记录一次, 并以 Excel 形式存 入电脑中; 电流 I(mA) 通过欧姆定律 I = U/R 计算 得到; 功率密度 $P(W \cdot m^{-3})$ 采用下式计算:

$$P = \frac{U_{\text{cell}}I}{V} = \frac{U_{\text{cell}}^2}{R_{\text{ov}}V} \tag{1}$$

式中, P 为体积功率密度, $\mathbf{W} \cdot \mathbf{m}^{-3}$; U_{cell} 为电池电压, \mathbf{V} ; V 为阳极室体积, \mathbf{m}^{3} ; R_{ev} 为外电阻, Ω .

极化曲线采用稳态法测定,先将ANAMMOX-MFC保持开路状态保持稳定后,逐步改变外电路电阻值9000~20 Ω ,外电阻减小幅度先大后小,9000~1000 Ω 之间时,每次减少1000 Ω ,1000~100 Ω 之间时,每次减少100 Ω ,100~20 Ω 之间时,每次减少20 Ω .记录ANAMMOX-MFC在每一外电阻下的稳定电压,通过数据采集卡记录并保存稳定状态下的电压值,并通过欧姆定律求得电流值,绘制相应的电压与电流的关系即可得到极化曲线;内阻选用稳态法测定,通过可变电阻箱改变外电阻20~9000 Ω ,得到稳定状态下的电压值和电流值,通过将极化曲线在欧姆极化区的数据拟合得到等效的表观内阻(又称电池内阻),同时在这个区域也可以得到最大的输出功率.

2 结果与分析

- 2.1 葡萄糖对 ANAMMOX-MFC 脱氮产电性能的 影响
- 2.1.1 葡萄糖对 ANAMMOX-MFC 脱氮性能的影响 设定葡萄糖浓度梯度为100、200、300、400、500 mg·L-1, 实验测得实际进水 COD 值分别为 125、 240、373、507、613 mg·L-1. 不同进水葡萄糖浓度对 ANAMMOX-MFC 的脱氮性能的影响如图 2 所示. 在 COD 浓度较低时(125~240 mg·L⁻¹), TN 去除率、 NH₄ -N去除率和去除速率、NO₂ -N去除率和去除速 率持续增加, ANAMMOX-MFC 阳极主要发生 ANAMMOX 反应,对 ANAMMOX-MFC 脱氮性能具有 一定促进作用; 当 COD 浓度上升至 $373 \text{ mg} \cdot \text{L}^{-1}$ 时, TN去除率、NH₄+-N去除率和去除速率开始出现下 降, 而NO, -N去除率和去除速率基本保持不变, 说明 ANAMMOX-MFC 阳极中厌氧氨氧化菌活性开始降 低,反硝化菌活性开始增强. 当 COD 浓度继续升高 至 613 mg·L⁻¹时, TN 去除率、NH₄ -N去除率和去除 速率继续下降, 而NO; -N去除率和去除速率基本保 持不变, 说明 ANAMMOX-MFC 阳极中厌氧氨氧化菌 活性继续下降, 反硝化作用不断增强.

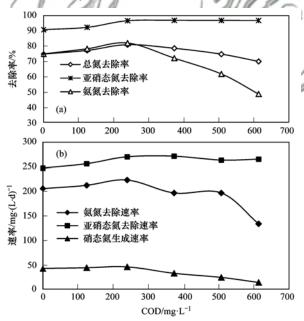
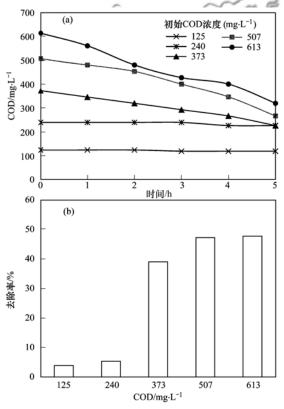


图 2 不同进水葡萄糖浓度对 ANAMMOX-MFC 的 脱氮性能的影响

Fig. 2 Effect of glucose concentration on the denitrification performance of ANAMMOX-MFC

设定葡萄糖浓度梯度为 $100 \, .200 \, .300 \, .400 \, .500 \, \text{mg·L}^{-1}$, 实验测得实际进水 COD 值分别为 $125 \, .240 \, .373 \, .507 \, .613 \, \text{mg·L}^{-1}$. 不同葡萄糖浓度

下 COD 变化如图 3 所示. 当进水 COD 浓度为 125 ~240 mg·L⁻¹时, 进出水 COD 浓度变化不大, 原因 在于 ANAMMOX-MFC 阳极异养细菌仍处于抑制状 态, 反应仍为厌氧氨氧化反应; 当进水 COD 浓度升 高至 373 mg·L⁻¹时, 出水 COD 浓度开始出现下降, 经过一个周期运行 COD 浓度从 373 mg·L-1降低至 227 mg·L⁻¹, COD 去除率为 39.1%; 当进水 COD 浓度继续升高至507 mg·L-1时, 经过一个周期运行 COD 浓度从 507 mg·L⁻¹降低至 267 mg·L⁻¹, COD 去除率为47.3%; 当进水 COD 浓度继续升高至613 mg·L-1时, 经过一个周期运行 COD 浓度从 613 mg·L⁻¹降低至320 mg·L⁻¹, COD 去除率为47.8%. 随着 COD 浓度的继续升高, 异养菌活性逐渐增强, COD 去除率和去除速率均升高,表明接种污泥中仍 存在异养细菌, 当进水葡萄糖浓度够高时异养细菌 会重新恢复活性.



- (a)不同葡萄糖浓度下周期内 COD 浓度变化;
- (b)不同葡萄糖浓度下周期内 COD 去除率变化

图 3 不同葡萄糖浓度下 COD 变化

Fig. 3 Change in COD under different concentrations of glucose

2.1.2 葡萄糖对 ANAMMOX-MFC 产电性能的影响 外电阻恒定为1 000 Ω, 设定葡萄糖浓度梯度 为 100、200、300、400、500 mg·L⁻¹, 实验测得实际 进水 COD 值分别为 125、240、373、507、613 mg·L⁻¹. 不同浓度 COD 对 ANAMMOX-MFC 产电性

能的影响如图 4 所示. 当 COD 浓度较低时(125~240 mg·L⁻¹),对产电性能有一定促进作用,ANAMMOX-MFC 的最大输出电压和最大输出功率密度从未投加葡萄糖时的(201.6 ± 2.9) mV 和(90.3 ± 1.3) mW·m⁻³上升至(240.1 ± 3.7) mV 和(128.1 ± 2.0) mW·m⁻³;当 COD 浓度升高至 373 mg·L⁻¹时,产电性能开始出现下降;当 COD 浓度继续升高至 613 mg·L⁻¹,ANAMMOX-MFC 的最大输出电压和最大输出功率密度降低至(131.0 ± 1.6) mV 和(38.1 ± 0.5) mW·m⁻³.

在每个 COD 条件下达到稳定后,通过改变电阻箱阻值9 000~20 Ω ,稳定状态下不同 COD 浓度条件下极化曲线的拟合如图 5 所示.表明 COD 浓

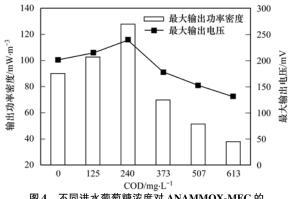


图 4 不同进水葡萄糖浓度对 ANAMMOX-MFC 的 产电性能的影响

Fig. 4 Effect of glucose concentration on the electrogenesis performance of ANAMMOX-MFC

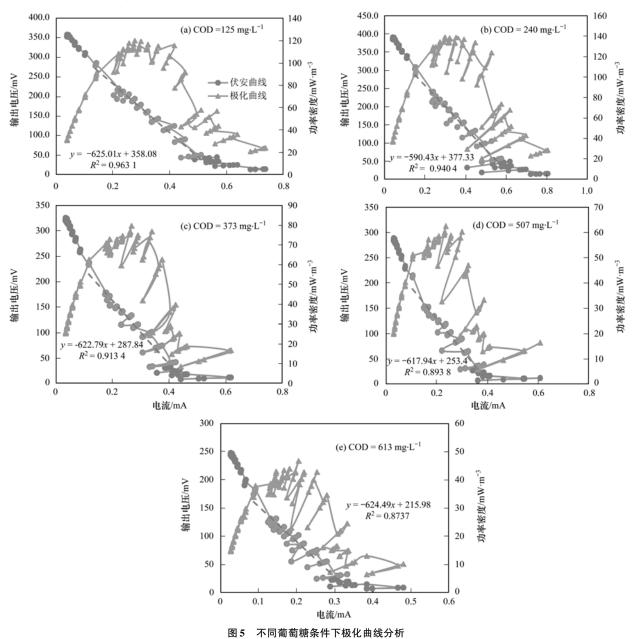


Fig. 5 Polarization curve analysis under different glucose conditions

度变化对电池内阻影响较小,对产电性能影响则较大. 当 COD 浓度较低时(125~240 mg·L⁻¹),最大输出电压和最大输出功率密度从(358.6±2.5)mV和(120.1±3.2)mW·m⁻³上升至(391.2±2.6)mV和(139.1±1.2)mW·m⁻³,对 ANAMMOX-MFC产电性能有一定促进作用;当 COD 浓度升高至 373mg·L⁻¹时,产电性能开始出现下降,最大输出电压和最大输出功率密度降低到(325.8±3.5)mV和(79.7±1.6)mW·m⁻³,并且输出电压比较难稳定,导致极化曲线拟合程度降低;当 COD 浓度继续升高至 613 mg·L⁻¹时,最大输出电压和最大输出功率密度降至(248.3±3.1)mV和(46.8±0.9)mW·m⁻³,极化曲线拟合程度继续降低.说明当COD 浓度过高时,会对 ANAMMOX-MFC 阳极生物反应产生影响,导致产电性能受到抑制且不稳定.

2.2 苯酚对 ANAMMOX-MFC 脱氮产电性能的影响 **2.2.1** 苯酚对 ANAMMOX-MFC 脱氮性能的影响

设定苯酚浓度梯度为 50、100、200、300、400 $mg \cdot L^{-1}$,实验测得实际 COD 值分别为 120、240、440、680、920 $mg \cdot L^{-1}$. 苯酚对 ANAMMOX-MFC 脱氮产电性能的影响如图 6 所示. 当 COD 浓度较低时($120 \sim 240$ $mg \cdot L^{-1}$),对 ANAMMOX-MFC 脱氮性能影响较低,TN 去除率为 71%, NH_{\star}^{+} -N去除率为

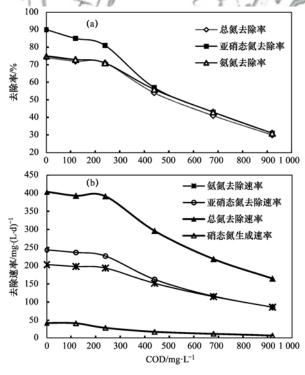
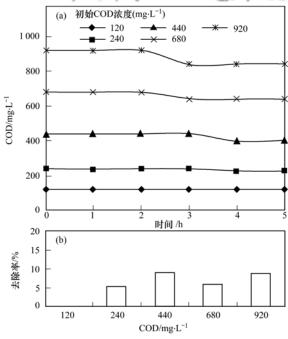


图 6 不同进水苯酚浓度对 ANAMMOX-MFC 的 脱氮性能的影响

Fig. 6 Effect of phenol concentration on the denitrification ${\bf performance\ of\ ANAMMOX-MFC}$

71%, NO_2^- -N去除率为81%; NH_4^+ -N、 NO_2^- -N和TN的去除速率为(193.6 ± 3.11)、(226.7 ± 2.8)和(391.1 ± 4.8) mg·(L·d) $^{-1}$;当 COD 浓度上升至440 mg·L $^{-1}$ 时脱氮效果开始出现抑制,TN 去除率为54%, NH_4^+ -N、 NO_2^- -N和TN的去除速率为(151.8 ± 2.3)、(162.5 ± 2.5)和(296.0 ± 4.5)mg·(L·d) $^{-1}$;当 COD 浓度继续升高至920 mg·L $^{-1}$,抑制作用逐渐增强, NH_4^+ -N、 NO_2^- -N和TN的去除率仅为31%, NO_2^- -N表除率仅为31%; NH_4^+ -N、 NO_2^- -N和TN的去除速率仅为(86.2 ± 1.6)、(86.3 ± 1.6)和(164.7 ± 3.1) mg·(L·d) $^{-1}$.

设定苯酚浓度梯度为 50、100、200、300、400 mg·L⁻¹,实验测得实际 COD 值分别为 120、240、440、680、920 mg·L⁻¹. 不同苯酚浓度下 COD 浓度变化如图 7 所示. 整个过程中 COD 浓度变化不大,说明苯酚不是 ANAMMOX-MFC 的反应基质.



- (a)不同苯酚浓度下周期内 COD 浓度变化;
- (b)不同苯酚浓度下周期内 COD 去除率变化

图 7 不同苯酚浓度下 COD 变化

Fig. 7 Change in COD under different concentrations of phenol

2.2.2 苯酚对 ANAMMOX-MFC 产电性能的影响

外电阻恒定为 1000 Ω 时,设定苯酚浓度梯度为 50、100、200、300、400 mg·L⁻¹,实验测得实际 COD 值分别为 120、240、440、680、920 mg·L⁻¹. 不同浓度 COD 对 ANAMMOX-MFC 产电性能的影响如图 8 所示. 当 COD 浓度较低时(120 ~ 240 mg·L⁻¹), ANAMMOX-MFC 的最大输出电压和最大

输出功率密度变化不大; 当进水 COD 浓度为 440 $mg \cdot L^{-1}$ 时, ANAMMOX-MFC 的最大输出电压和最大输出功率密度开始出现下降; 最终当进水 COD 浓度升高至 920 $mg \cdot L^{-1}$ 时, ANAMMOX-MFC 的最大输出电压和最大输出功率密度降低至(100.7 ± 2.0)mV 和(22.5 ± 0.5) $mW \cdot m^{-3}$.

在每个 COD 条件下达到稳定后,通过改变电阻箱阻值(9000~20 Ω),稳定状态下对不同 COD 条件下极化曲线的拟合如图 9 所示. 表观内阻缓慢升高的原因有待进一步研究,R 值较低,原因在于 ANAMMOX-MFC 阳极反应受到抑制,破坏了原有的稳定状态. 当 COD 浓度较低时(120~240 mg·L⁻¹),对 ANAMMOX-MFC 产电性能影响较小;当 COD 浓度升高至 440 mg·L⁻¹时,产电性能开始出现下降,当 COD 浓

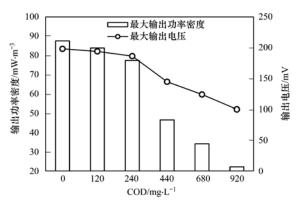


图 8 不同进水苯酚浓度对 ANAMMOX-MFC 的 产电性能的影响

Fig. 8 Effect of phenol concentration on the electrogenesis performance of ANAMMOX-MFC

度继续升高至 920 $mg \cdot L^{-1}$, 产电性能受到抑制, 最大输出电压为(200.0 ± 2.2) mV, 最大输出功

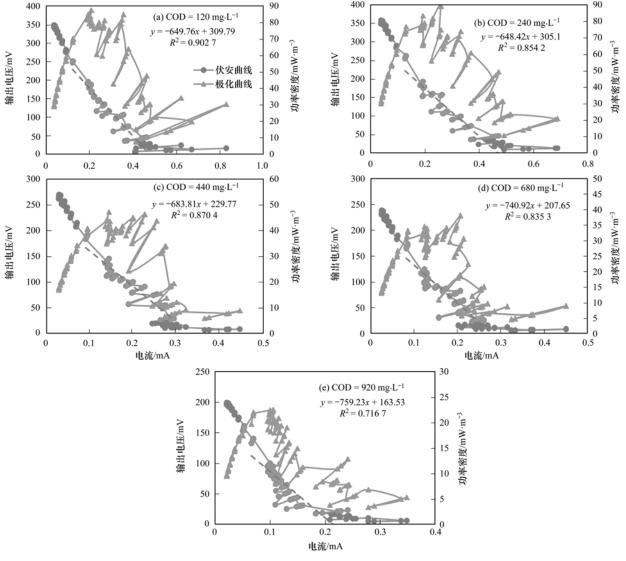


图 9 不同苯酚条件下极化曲线分析

Fig. 9 Polarization curve analysis under different phenol conditions

率密度为(22.6±0.6) mW·m⁻³, 且输出电压很难长时间处于稳定状态.

3 讨论

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本研究结果表明: 当采用葡萄糖来调控废水中COD浓度时,当COD浓度达到373 mg·L⁻¹时会抑制厌氧氨氧化反应,本研究结果与前人^[19,20]研究

的抑制浓度有所差异, COD 抑制浓度有所不同可能是接种污泥和反应器有所差异引起的, 本实验采用ANAMMOX-MFC 反应器, 该反应器能同时脱氮产电. 当苯酚浓度超过 200 mg·L⁻¹时会抑制厌氧氨氧化反应, 苯酚抑制浓度与前人研究有所不同^[21,22]可能是反应器有所差异引起的. 表 2 给出了影响厌氧氨氧化反应的相关研究.

表 2 影响厌氧氨氧化反应的相关研究结果

Table 2 Related research results affecting ANAMMOX reaction

反应器	接种污泥	调控 COD 浓度的物质	抑制厌氧氨氧化 反应的 COD 浓度/mg·L ⁻¹	抑制厌氧氨氧化 反应的苯酚浓度/mg·L ⁻¹	文献
UASB	厌氧污泥和厌氧氨氧化污泥	全脂牛奶	300	/	[19]
ASBR	好氧硝化污泥	葡萄糖	200	/	[20]
SBR	厌氧氨氧化污泥	/	/	300	[21]
血清瓶	厌氧氨氧化污泥	/	/	600	[22]
ANAMMOX-MFC	厌氧氨氧化污泥	葡萄糖 苯酚	373 440	200	本研究

An 等^[23]在将实际废水进入 MFC 之后,发现随着最大功率密度的降低,而相应地内阻增加. Li 等^[24]将厌氧氨氧化和脱氮微生物燃料电池耦合,在稳定运行时产生连续的电流密度为 165 mA·m⁻². Lee 等^[8]使用 MFC/Anammox 反应器处理垃圾渗滤液,产生的最大功率密度达 12 mW·m⁻³.

4 结论

- (1) 当葡萄糖浓度较低时(125~240 mg·L⁻¹), 对 ANAMMOX 菌有促进作用, ANAMMOX-MFC 脱氮产电性能增强, 此时反应器进出水 COD 变化不大; 当葡萄糖浓度高于 300 mg·L⁻¹时, 产电性能逐渐下降, NH_4^+ -N去除率和去除速率逐渐下降, 而 NO_2^- -N去除率和去除速率基本保持不变, 此时出水 COD 浓度也出现降低, 说明厌氧氨氧化菌活性受到抑制, 反硝化菌活性开始增强.
- (2)当用葡萄糖来调控废水中 COD 浓度时,随着 COD 浓度的增加极化曲线拟合程度降低; COD 浓度变化对电池内阻影响较小,对产电性能影响较大.
- (3) 当苯酚浓度较低时(50~100 mg·L⁻¹),对 ANAMMOX-MFC 脱氮产电性能影响较低;当苯酚浓度超过 200 mg·L⁻¹时,ANAMMOX-MFC 脱氮产电性能逐渐被抑制.
- (4)当用苯酚来调控废水中 COD 浓度时,整个过程进出水 COD 浓度变化不大,极化曲线拟合程度较低,表观内阻有缓慢升高.

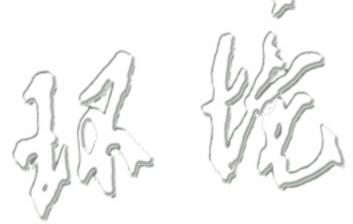
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