



EGSB 处理垃圾焚烧厂渗滤液的启动与运行研究

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[摘要] 研究了采用EGSB反应器处理稀释垃圾焚烧厂渗滤液快速启动与运行过程,并对初期与末期厌氧颗粒污泥的物化特征进行对比分析。研究表明,在接种颗粒污泥的情况下EGSB反应器22 d完成快速启动;反应器经过180 d的运行,在COD容积负荷为 $15 \text{ kg}/(\text{m}^3 \cdot \text{d})$ 、回流比为800%、HRT为8 h、反应器内部温度为 $30\sim 35^\circ\text{C}$ 的条件下,对渗滤液COD的去除率达到90%以上,色度去除率为75%左右,此外,日产气量达到150 L左右,与理论计算值($72\sim 150 \text{ L/d}$)基本一致,反应器运行状态良好。扫描电镜分析结果表明,颗粒污泥接种时内部丝状菌较多,球菌与短杆菌数量较少,内部结构松散;运行结束后以球菌和短杆菌为主,厌氧颗粒污泥内部结构紧密厚实,内部孔隙较接种时明显增多。高通量测序结果表明,与接种时相比,运行结束后颗粒污泥内的微生物种群数量和丰富度都大幅增加,拟杆菌门成为厌氧颗粒污泥内的主要优势菌种。

[关键词] 垃圾渗滤液;EGSB反应器;厌氧颗粒污泥

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Study on start-up and operation of EGSB in treating leachate from waste incineration plant

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Abstract: The rapid start-up and operation process of the EGSB reactor used to treat the leachate from a waste incineration plant was studied, and the physical and chemical characteristics of anaerobic granular sludge at the initial and final stages were compared and analyzed. The results showed that the rapid start-up of the EGSB reactor was completed in 22 days with the inoculation of granular sludge. After 180 days of operation, the COD removal rate of leachate reached more than 90% and the chroma removal rate was about 75%, at COD volumetric loading of $15 \text{ kg}/(\text{m}^3 \cdot \text{d})$, a reflux ratio of 800%, HRT of 8 h, and an internal temperature of $30\sim 35^\circ\text{C}$. In addition, the daily gas production reached about 150 L, which was basically consistent with the theoretical calculation value ($72\sim 150 \text{ L/d}$), and the reactor was in good operating condition. The results of scanning electron microscope analysis showed that there were more filamentous bacteria inside the granular sludge at the time of inoculation, and the number of cocci and bacilli was less, and the internal structure was loose. At the end of the operation, the internal structure of the anaerobic granular sludge was thicker and more pores than at the time of inoculation. The high-throughput sequencing results showed that the number and abundance of microbial populations in the granular sludge increased significantly at the end of the operation compared with that at the time of inoculation. The phylum Bacillus became the main dominant species in the anaerobic granular sludge.

Key words: waste incineration leachate; EGSB reactor; anaerobic granular sludge

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垃圾焚烧技术因无害化、减量化和资源化的优势,近年来成为我国城市生活垃圾处理的主流技术之一^[1]。数据显示^[2],我国生活垃圾年产生量高达24 206万t,其中通过焚烧发电处理的生活垃圾已达到总量的50%。在焚烧过程中,渗滤液产量达到生活垃圾总量的12%~23%^[3],引起严重的环境问题。

目前垃圾焚烧厂大多采用厌氧+好氧+深度处理的组合工艺^[4-9]。其中厌氧处理能有效降解渗滤液中的大量有机物(COD去除率大多在60%以上),是垃圾焚烧渗滤液处理工艺的核心。

值得关注的是,若直接采用厌氧系统处理垃圾焚烧渗滤液原液,过高的盐度(Cl⁻质量浓度达到10 000 mg/L)会严重抑制厌氧菌群活性,导致有机物去除效果降低^[10],同时产生的沉积盐容易造成系统管道堵塞与腐蚀,产生一系列技术难题。笔者课题组采用上流式厌氧污泥床(UASB)反应器处理稀释后的垃圾焚烧厂渗滤液,发现进水COD为5 000 mg/L时,UASB反应器对COD的去除率达到85%左右^[11],去除效果十分明显。通过稀释垃圾焚烧厂渗滤液可以有效降低进水盐度,提高系统稳定性及微生物活性,更利有机污染物的去除。

与UASB反应器相比,EGSB反应器采用大比例循环水,对COD的适应范围更大,处理效果更好,启动周期更短,颗粒污泥强度更强,污泥流失量更少^[12],适于超高浓度废水的处理,可有效降低COD与盐度。笔者研究了EGSB反应器对稀释渗滤液的处理过程,对厌氧颗粒污泥内的微生物种群进行分析,以期对相关研究与工程应用提供借鉴。

1 材料与方法

1.1 实验水质

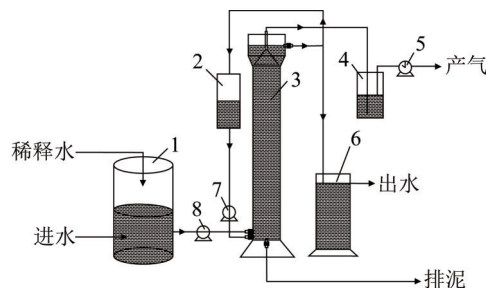
垃圾渗滤液取自西安某垃圾焚烧发电厂初沉池,经手动篮式过滤器2 mm格栅去除大颗粒悬浮物,其水质情况为:COD 65 000~82 000 mg/L、BOD₅ 35 000~40 000 mg/L、NH₃-N 1 000~1 500 mg/L、SS 1 800~4 000 mg/L、碱度 14 000~16 000 mg/L、pH 5~6。

1.2 接种污泥

接种颗粒污泥取自西安某淀粉厂UASB反应器,污泥质量浓度38 g/L,VSS/TSS为0.72,颗粒污泥粒径平均在2 mm。污泥接种量为9 L,占EGSB反应器有效容积的45%。

1.3 EGSB反应器

实验所用EGSB反应器高1.8 m,内径120 mm,有效容积为20.5 L,底端侧边设有进水口、循环口及排泥口,顶端设三相分离器,水浴保持进水温度在28~35℃。其结构见图1。



1—调节池;2—循环罐;3—EGSB反应器;4—除CO₂罐;5—湿式气体流量计;6—初沉池;7—循环泵;8—进液泵。

图1 EGSB工艺流程

Fig. 1 Process flow of EGSB

1.4 分析方法

COD采用快速消解法测定,VFA采用蒸馏滴定法测定,色度采用稀释倍数法测定,产气量由湿式气体流量计记录,pH采用pHBJ-260型pH计(上海仪电科学仪器股份有限公司)测定,盐度采用DDSJ-308A电导率仪(上海仪电科学仪器股份有限公司)测定。

用扫描电镜(SEM)对颗粒污泥进行微观分析,通过上海生工 Illumina Miseq2×300 bp 测序平台进行微生物测序分析,测序方法见文献[13]。

2 结果与分析

2.1 EGSB反应器对稀释渗滤液COD的去除效果

采用容积负荷和上升流速交替提高的方式运行反应器,对运行过程中进出水的COD变化情况进行监测。整个运行过程持续180 d,主要分为4个阶段:驯化启动阶段(I)、试运行阶段(II)、负荷提高阶段(III)及稳定运行阶段(IV)。其运行结果见图2。

由于该渗滤液具有一定的厌氧毒性,初期为保证接种颗粒污泥适应该渗滤液水质^[14],采用清水稀释的方式进行EGSB启动[阶段I]。反应器启动时进水COD为1 580 mg/L,COD容积负荷为1.5 kg/(m³·d),保持HRT为24 h,上升流速为0.15 m/h运行2 d,COD去除率达到90%以上。调整进水COD为750 mg/L左右,22 d后反应器COD容积负荷达到15 kg/(m³·d),上升流速为2 m/h,COD平均去除率达

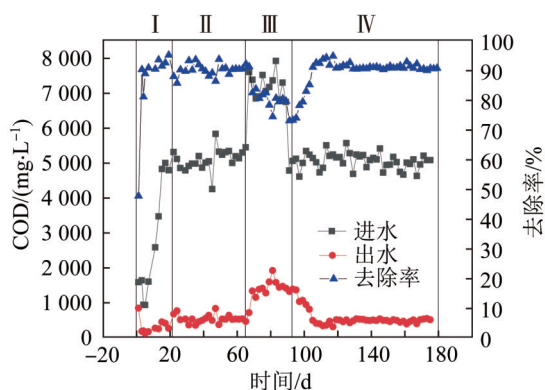


图2 运行阶段EGSB的进出水COD及去除率

Fig. 2 COD and removal rate of EGSB inlet and outlet water during operation

到90%,系统运行稳定。EGSB反应器经过22 d的运行驯化完成。

污泥驯化完成进入系统试运行阶段[阶段Ⅱ, 22~62 d], 进水COD为5 000 mg/L, COD容积负荷为15 kg/(m³·d), 反应器出水COD始终保持在500 mg/L左右, 表明颗粒污泥的微生物活性高, 对该渗滤液表现出较强的适应能力。

运行第63天时提升反应器容积负荷[阶段Ⅲ, 63~92 d], 将进水COD从5 000 mg/L提升至7 000 mg/L, 容积负荷从15 kg/(m³·d)升至21 kg/(m³·d), 保持HRT和上升流速不变, 第87天时COD去除率维持在82%左右。继续运行至90 d, COD去除率降至73%。其原因可能为随着厌氧反应器负荷的迅速升高, 进水水质变化导致颗粒污泥破裂^[15], 出水口泥水分离不均, 同时进水过高的盐度会抑制微生物活性, 导致微生物对有机碳降解能力下降^[10], 从而出现“跑泥”现象。

从第93天开始[阶段Ⅳ, 93~180 d], 为保证系统稳定性, 将进水COD重新调整至5 000 mg/L, 容积负荷调整为15 kg/(m³·d), 19 d后COD去除率恢复到90%以上, 此时反应器出水COD稳定在500 mg/L左右。

在系统运行期间, 测定厌氧进水色度为128倍, 出水仅为32倍, 色度去除率达到75%。

李进等^[11]采用4.2 L UASB反应器处理垃圾焚烧厂渗滤液, 在垃圾焚烧厂渗滤液稀释10倍、进水COD为5 000 mg/L条件下, COD去除率达到85%左右, 容积负荷为2.33~5.30 kg/(m³·d)。与其研究结果相比, 可发现在相似稀释倍数及进水COD的条件下, EGSB反应器对COD的去除效果明显高于UASB反应器, 说明EGSB反应器大比例循环水更有利于

去除稀释垃圾焚烧厂渗滤液中的COD。

2.2 VFA、产气量、pH和容积负荷的变化情况

VFA、pH等参数可很好地反映EGSB反应器内微生物活性和有机物去除效果。运行期间反应器内pH和容积负荷的变化情况如图3所示。

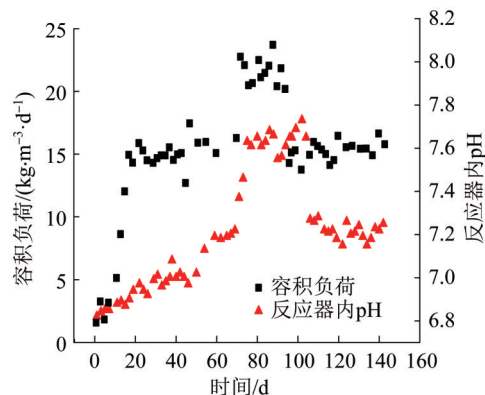


图3 反应器内pH和容积负荷的变化

Fig. 3 Changes in pH and volumetric loading in the reactor

如图3所示, 当容积负荷从1.5 kg/(m³·d)提升至21 kg/(m³·d), 反应器内pH稳定在6.8~8.2; 容积负荷从21 kg/(m³·d)调整至15 kg/(m³·d)后, 反应器内pH迅速降至7.2左右, 表明容积负荷对反应器内pH影响较大, 同时反应器内颗粒污泥具有很强的pH缓冲能力, 并未因环境改变而出现酸化现象。

从第40天开始监测反应器内VFA和产气量, 结果见图4。

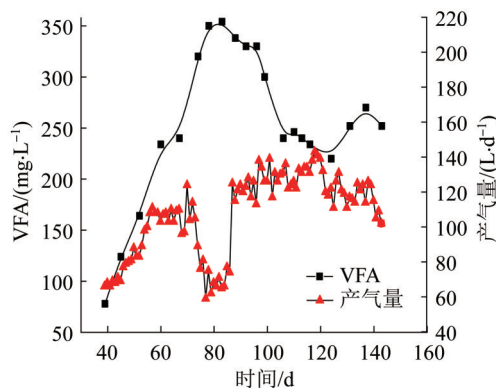


图4 VFA及产气量变化情况

Fig. 4 Changes in VFA and gas production

由图4可见, 运行期间反应器内VFA维持在78~354 mg/L(以乙酸计), 甲烷产量维持在78~160 L/d, 与理论值(72~150 L/d)基本相符。这表明运行过程中产甲烷菌一直保持较高活性, 能较快降解产酸菌产生的VFA。

在运行过程中,颗粒污泥经过长时间培养对容积负荷冲击和VFA的耐受能力增强,EGSB大比例循环回流对反应器内VFA有稀释作用^[16],有利于EGSB反应器pH的稳定。

2.3 厌氧颗粒污泥物理性质分析

实验结束后对EGSB底部颗粒污泥的表观形态进行观察,如图5所示。可见经过长时间培养形成椭球或圆球状厌氧颗粒污泥,平均粒径为1~2 mm,表面光滑,呈黑色或黑灰色。

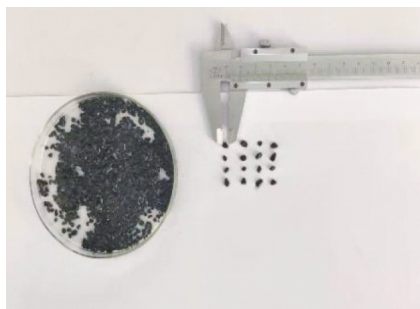


图5 颗粒污泥表观形态

Fig. 5 Morphology of granular sludge

为进一步分析厌氧颗粒污泥内部结构和微生物形态,对运行前后的颗粒污泥进行SEM观察,结果见图6。

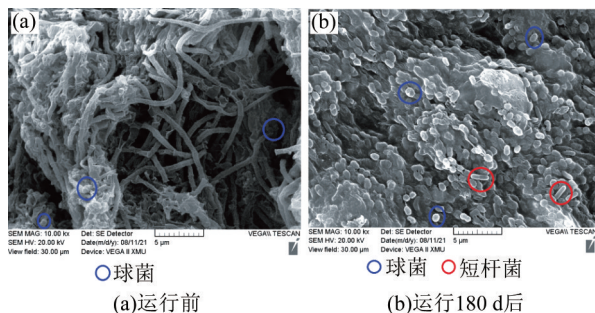


图6 运行前后颗粒污泥的SEM照片

Fig. 6 SEM images of granular sludge before and after operation

由图6(a)可见,运行前,颗粒污泥内部菌群以丝状菌为主,含有少量球菌,微生物种类和数量较少,污泥内部组织结构疏松,呈絮体状,有一定孔隙。

处理渗滤液后,颗粒污泥内部结构发生较大变化,污泥内部结构紧密厚实,内部传质通道明显增多,有利于厌氧颗粒污泥内部传质过程的强化^[17]。同时微生物种类呈现多样化,其中丝状菌含量减少,球菌和短杆菌数量增多,不同的菌落随机分布相互交融,形成混栖的菌群。这种结构有利于菌体间营

养物质的传递、吸收及代谢,为有机物降解创造了有利条件^[18]。

2.4 颗粒污泥的生物学特征

为研究运行前后厌氧颗粒污泥内微生物种群的变化情况,对颗粒污泥16S rDNA高变区V3~V4区进行高通量测序分析。其物种种群分布及相对丰度情况如图7所示,G1、G2分别代表运行前接种污泥和运行结束后的污泥样品。

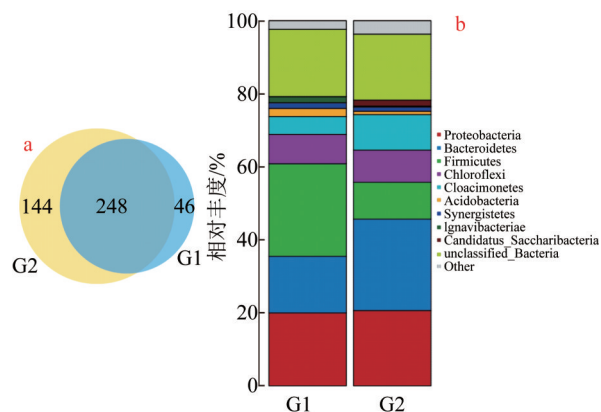


图7 运行前后颗粒污泥内物种分布(a)及相对丰度(b)

Fig. 7 Species distribution (a) and relative abundance (b) within granular sludge before and after operation

如图7(a)所示,运行前后颗粒污泥物种的丰富度有很大变化,运行前颗粒污泥微生物种群共294种,运行结束后微生物种群增加至392种,其中两者共有248种微生物种群,颗粒污泥内功能菌群相对丰度明显增加。图7(b)显示了运行前后颗粒污泥的微生物群落组成,其中变形菌门(Proteobacteria)、拟杆菌门(Bacteroidetes)、厚壁菌门(Firmicutes)、绿弯菌门(Chloroflexi)、阴沟单胞菌门(Cloacimonetes)和未分类细菌(unclassified-Bacteria)在G1、G2中的占比均较高。

对垃圾焚烧渗滤液进行处理后,颗粒污泥中的优势菌种发生明显变化,其中Bacteroidetes占25%,Proteobacteria占20.65%,unclassified-Bacteria占18.05%,而Firmicutes丰度占比从25.33%降至10.11%,成为反应器运行后颗粒污泥中的第四大菌群。作为运行后颗粒污泥内的最优势菌种,Bacteroidetes属于革兰氏阴性厌氧菌,主要将废水中的多糖类碳水化合物水解转化为乙酸、异戊酸和琥珀酸^[19]。运行前后优势菌种的转变表明渗滤液中多糖类物质居多。G2中Proteobacteria主要为 δ -变形菌,属水平上又以脱硫弧菌(*Desulfovibrio*)

居多,这类菌可将可还原态硫化物转化为硫化氢。由于垃圾焚烧厂渗滤液中大量存在的硫酸盐被硫酸盐还原细菌还原,使得厌氧反应器运行过程中存在一定量硫化物^[20]。

Yan DANG等^[21]采用EGSB反应器处理未稀释的垃圾焚烧厂渗滤液,容积负荷为 $18\text{ kg}/(\text{m}^3\cdot\text{d})$ 时,COD去除率达到86.7%,但受垃圾焚烧厂渗滤液水质影响,其真菌种类和数量相对较低,微生物种类只达到138种,且颗粒污泥中Firmicutes为最优势菌种,表明高浓度垃圾焚烧厂渗滤液对厌氧菌群有较大的抑制作用。本研究的颗粒污泥中微生物种类可达392种,Bacteroidetes成为最优势菌种,说明对于高浓度垃圾焚烧厂渗滤液,采用清水稀释的方式可较好地减少其对微生物的抑制作用,有利于微生物种群丰富度的提高以及有机污染物的去除。

3 结论

(1)用EGSB反应器对稀释垃圾焚烧厂渗滤液进行处理,进水COD为 $5\ 000\text{ mg/L}$ 、容积负荷为 $15\text{ kg}/(\text{m}^3\cdot\text{d})$ 时,COD去除率高达90%以上。

(2)EGSB反应器运行前,颗粒污泥内的微生物种群为294种;运行后以球菌、短杆菌为主,微生物种群增至392种,微生物相对丰度增加较大,同时颗粒污泥内Bacteroidetes成为优势菌群,Firmicutes所占比例大幅降低。

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