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低温 SNAD 颗粒污泥工艺启动方式

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摘要: 为研究启动方式对同步短程硝化、厌氧氨氧化耦合反硝化(SNAD)颗粒污泥工艺的影响, 低温(12.7~18.3℃)条件下, R1和R2反应器分别通过先启动全程自养脱氮(CANON)工艺和先启动厌氧氨氧化耦合反硝化(SAD)工艺的方式逐步启动SNAD颗粒污泥工艺。结果表明, R1反应器启动成功后, 氨氮几乎完全去除, 总氮去除率达到86.7%。低氨氮浓度运行时, 出水总氮去除率下降至75.3%, 出水总氮浓度在10 mg·L⁻¹左右, NOB存在过量增殖现象, 出水总氮浓度超过北京市水污染物排放标准一级A规定。R2反应器启动成功后, 出水几乎不含氨氮, 总氮去除率在89.1%左右, 略高于R1反应器。低氨氮浓度运行时, 出水氨氮浓度小于1.0 mg·L⁻¹, 出水总氮浓度小于6 mg·L⁻¹, 出水氨氮和总氮浓度满足地标一级A标准。先启动SAD工艺可以在启动初期通过厌氧运行将NOB逐渐淘汰出系统内, 维持了系统的稳定性, 为后续曝气启动SNAD工艺提供了良好的基础, 维持了反应器的稳定运行, 实现出水总氮长期排放达标。

关键词: 同步短程硝化、厌氧氨氧化与反硝化(SNAD); 颗粒污泥; 启动方式; 低温

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Startup Strategies for the SNAD Granular Sludge Process at Low Temperature

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Abstract: To study the effect of the startup strategies on the simultaneous partial nitrification, ANAMMOX, and denitrification (SNAD) granular sludge processes, these processes were initiated by starting the completely autotrophic nitrogen removal over nitrite (CANON) process and anaerobic ammonia oxidation-denitrification (SAD) process at 12.7°C and 18.3°C, respectively. The results show that the ammonia nitrogen was almost completely removed and the total nitrogen removal rate reached 86.7% after the R1 reactor was successfully started. When the ammonia concentration was low, the total nitrogen removal rate in the effluent decreased to 75.3%, the total nitrogen concentration in the effluent was ~10 mg·L⁻¹, and excessive proliferation of the NOB was observed. The total nitrogen concentration in the effluent exceeded the 1A level of the integrated discharge standard of water pollutants applied in Beijing City. After the R2 reactor was successfully started, the effluent contained almost no ammonia nitrogen and the total nitrogen removal rate was ~89.1%, that is, slightly higher than that of the R1 reactor. When the ammonia concentration was low, the concentration of ammonia nitrogen in effluent was less than 1.0 mg·L⁻¹ and the total nitrogen concentration in the effluent was less than 6 mg·L⁻¹. The concentrations of ammonia nitrogen and total nitrogen in the effluent reached the 1A level of the integrated discharge standard of water pollutants applied in Beijing City. First, the startup of the SAD process gradually eliminated the NOB from the system through anaerobic operation in the initial stage of the startup, maintained the stability of the system, provided a good basis for the subsequent aeration to start the SNAD process, maintained the stable operation of the reactor, and the long-term discharge of total nitrogen reached the standard.

Key words: simultaneous partial nitrification, ANAMMOX, and denitrification (SNAD); granular sludge; startup strategies; low temperature

同步短程硝化、厌氧氨氧化与反硝化(simultaneous partial nitrification, ANAMMOX, and denitrification, SNAD)工艺解决了传统脱氮工艺能源消耗高、污泥产量高等问题,也解决了全程自养脱氮工艺出水硝酸盐氮含量高的弊端,是一种极具前景的污水脱氮工艺^[1]。

厌氧氨氧化菌的最适生长温度范围为30~40℃^[2-5],国内外大部分研究在高温条件下进行,但污水处理厂进水水温一般在15~20℃左右,因此需要对该温度条件下的污泥反应活性等进行研究。SNAD工艺的核心为厌氧氨氧化反应,厌氧氨氧化菌

生长缓慢,富集困难^[6-8],使厌氧氨氧化菌保留在反应器中对反应器的正常运行至关重要^[9-11]。颗粒化可以将大部分污泥持留在反应器内,且抗冲击负荷能力及沉降性能较强^[12-14]。目前大部分研究集中在改变运行条件运行SNAD颗粒污泥工艺,而通过改变启动策略启动并运行SNAD工艺的研究较少。

低温低氨氮环境中,SNAD工艺的难点在于对

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硝化细菌的抑制^[15, 16]. 如果硝化细菌过量增殖, 将会导致总氮去除率下降、出水总氮超标. 只调节 DO 从而抑制 NOB 活性已被证明难以实现. 但先启动全程自养脱氮(CANON)工艺会导致初期 NOB 的含量就处于较高水平, 难以抑制. 研究表明^[17-19], 低温、低游离氨条件下, 单纯通过低 DO 抑制 NOB 活性难以实现, 而厌氧运行对 NOB 有很好的抑制作用, 先启动 SAD 工艺可以通过厌氧运行将 NOB 活性抑制在较低水平, 有效降低出水硝氮浓度.

因此本研究提出在低温条件下, 采用先启动 SAD 工艺再耦合亚硝化的方式启动 SNAD 颗粒污泥工艺, 随后逐渐降低进水氨氮浓度使其适应生活污水水质, 分析低温条件下不同启动方式及低氨氮浓度对 SNAD 颗粒污泥工艺脱氮性能、粒径和 EPS 等方面的影响.

1 材料与方法

1.1 接种污泥

反应器接种厌氧氨氧化污泥和污水处理厂 A/O 工艺污泥混合污泥, 比例为 1:1, 共接种污泥 1.6 L. 厌氧氨氧化污泥浓度为 $6\ 237\ \text{mg}\cdot\text{L}^{-1}$, 接种污泥 600 mL; 污水处理厂 A/O 工艺污泥浓度为 $3\ 862\ \text{mg}\cdot\text{L}^{-1}$, 接种污泥 1 000 mL.

1.2 实验用水

本实验进水为人工配水, 在进水中添加 $\text{NH}_4(\text{SO}_4)_2$ 、 NaNO_2 和丙酸钠提供进水氨氮、亚硝氮和 COD, 同时投加 NaHCO_3 提供无机碳源及调整碱度, 保持 pH 在 7.0 ~ 8.0. $\text{MgSO}_4\cdot 7\text{H}_2\text{O}$ $5\ \text{mg}\cdot\text{L}^{-1}$, K_2HPO_4 $2\ \text{mg}\cdot\text{L}^{-1}$, $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$ $3\ \text{mg}\cdot\text{L}^{-1}$, 微量元素浓缩液 $1.0\ \text{mL}\cdot\text{L}^{-1}$. 微量元素浓缩液 I 的组成 ($\text{g}\cdot\text{L}^{-1}$): EDTA 5, FeSO_4 5; 微量元素浓缩液 II 的组成 ($\text{g}\cdot\text{L}^{-1}$): EDTA 15, H_3BO_4 0.014, $\text{MnCl}_2\cdot 4\text{H}_2\text{O}$ 0.99, $\text{CuSO}_4\cdot 5\text{H}_2\text{O}$ 0.25, $\text{ZnSO}_4\cdot 7\text{H}_2\text{O}$ 0.43, $\text{NaSeO}_4\cdot 10\text{H}_2\text{O}$ 0.21, $\text{NaMoO}_4\cdot 2\text{H}_2\text{O}$ 0.22, $\text{CoCl}_2\cdot 6\text{H}_2\text{O}$ 0.24, $\text{NiCl}_2\cdot 6\text{H}_2\text{O}$ 0.19.

1.3 实验装置

本实验采用两个相同的 SBR 反应器, 分别为 R1、R2. 反应器由有机玻璃制成, 有效容积 6.0 L,

反应器壁上的垂直方向每隔 5 cm 设置一个取样口. 采用机械搅拌, 每个反应器内底部设有曝气盘, 通过气体流量计控制曝气量. 反应器实验装置示意如图 1 所示. 反应器的运行通过时控开关进行控制, 容积交换率为 2/3.

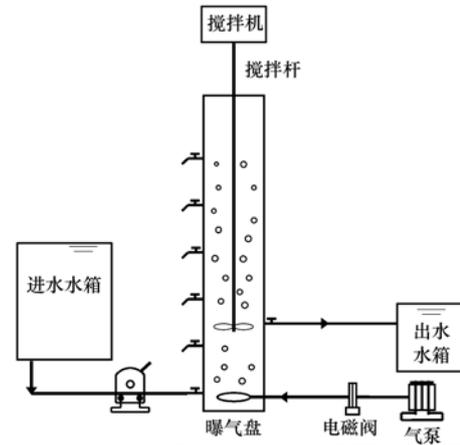


图 1 反应器装置示意

Fig. 1 Schematic diagram of the experimental equipment

1.4 运行策略

本实验在两个反应器内进行, R1 反应器的运行分为 4 个阶段. S1(1 ~ 44 d)为 CANON 工艺的启动阶段, 对反应器进行曝气启动 CANON 工艺; S2(45 ~ 98 d)为 SNAD 颗粒污泥工艺启动阶段, 在进水中添加有机碳源启动 SNAD 颗粒污泥工艺; S3(99 ~ 112 d)为进水氨氮浓度为 $80\ \text{mg}\cdot\text{L}^{-1}$, SNAD 颗粒污泥稳定运行阶段; S4(113 ~ 145 d)为进水氨氮浓度为 $40\ \text{mg}\cdot\text{L}^{-1}$ 时, SNAD 颗粒污泥稳定运行阶段.

R2 反应器分为 4 个阶段, S1(1 ~ 44 d)为 SAD 工艺的启动阶段, 在进水中添加有机碳源启动 SAD 工艺; S2(45 ~ 98 d)为 SNAD 颗粒污泥工艺的启动阶段, 对反应器进行曝气启动 SNAD 颗粒污泥工艺; S3(99 ~ 112 d)为进水氨氮浓度为 $80\ \text{mg}\cdot\text{L}^{-1}$, SNAD 颗粒污泥稳定运行阶段; S4(113 ~ 145 d)为进水氨氮浓度为 $40\ \text{mg}\cdot\text{L}^{-1}$ 时, SNAD 颗粒污泥稳定运行阶段. 不同阶段进水水质指标如表 1 所示.

1.5 水质监测参数及分析方法

本实验中 NH_4^+-N 采用纳氏试剂光度法; NO_2^--N

表 1 实验各阶段水质及操作参数/ $\text{mg}\cdot\text{L}^{-1}$

Table 1 Influent substrate and operational conditions at various periods/ $\text{mg}\cdot\text{L}^{-1}$

阶段	R1 反应器			R2 反应器		
	NH_4^+-N	NO_2^--N	COD	NH_4^+-N	NO_2^--N	COD
S1(1 ~ 44 d)	120	0	0	120	120	100
S2(45 ~ 98 d)	120	0	100	120	0	100
S3(99 ~ 112 d)	80	0	100	80	0	100
S4(113 ~ 145 d)	40	0	100	40	0	100

采用 *N*-(1-萘基)乙二胺光度法测定; NO_3^- -N 采用紫外分光光度法; pH 值、DO 及温度测定采用便携式的 WTWpH/Oxi 340i 测定仪测定; COD 采用 COD 快速测定仪测定; 粒径采用 Mastersize2000 型激光粒度仪测定; EPS 中 PS 采用苯酚-硫酸比色法; PN 采用考马斯亮蓝法; 混合液悬浮固体浓度 (MLSS); 挥发性悬浮固体浓度 (MLVSS) 采用标准重量法测定^[20]; 其余水质指标的分析方法均采用国标方法; 进水泵采用兰格恒流蠕动泵。

2 结果与讨论

2.1 不同启动方式 SNAD 颗粒污泥工艺脱氮性能对比

本实验在低温条件下采用两种不同的启动方法启动 SNAD 颗粒污泥工艺, 将污水处理厂 A/O 工艺污泥与厌氧氨氧化污泥混合, 分别装入 R1、R2 两个反应器内, 反应器内水温在 12.7 ~ 18.3℃。在 R1 反应器内接入曝气装置, 首先启动 CANON 工艺, 随后在进水中添加丙酸钠启动 SNAD 工艺; R2 反应器先厌氧运行, 在进水中添加丙酸钠启动 SAD 工艺, 随后曝气启动 SNAD 工艺。R1、R2 反应器进水基质浓度如表 1 所示。

R1 反应器进出水基质浓度变化如图 2 所示, 反应器进出水总氮变化及总氮去除率如图 3 所示。有研究表明^[21], AOB 对 DO 的亲合力较 NOB 强, AOB 氧饱和常数一般为 0.2 ~ 0.4 $\text{mg}\cdot\text{L}^{-1}$, NOB 氧饱和常数为 1.2 ~ 1.5 $\text{mg}\cdot\text{L}^{-1}$, 低 DO 浓度可以抑制 NOB 活性, 但对 AOB 基本没有影响, 为了减少 DO 对厌氧氨氧化菌的抑制以及抑制硝化细菌的活性, 将 R1 反应器内 DO 浓度保持在 0.5 $\text{mg}\cdot\text{L}^{-1}$ 左右, 以抑制 NOB 的生长并富集 AOB。

由于接种了部分污水厂污泥, 异养菌较多, 启动初期出水水质波动较大, 部分异养菌难以适应新环境, 细胞解体导致出水 COD 浓度升高, 并且出水氨氮浓度较高。由图 3 可见, S1 阶段反应器内温度较低, 微生物活性恢复较慢, 总氮去除率较低。第 17 d 时, 出水氨氮浓度减少至 10.6 $\text{mg}\cdot\text{L}^{-1}$, 氨氮去除率大于 90%, 总氮去除率为 81.9%, AOB 活性逐渐恢复, 为厌氧氨氧化菌提供基质, 出水氨氮浓度稳定在 1 $\text{mg}\cdot\text{L}^{-1}$ 以下, 随着厌氧氨氧化菌活性逐渐恢复, 出水硝氮浓度进一步增加, 保持在 14.3 $\text{mg}\cdot\text{L}^{-1}$ 左右。第 35 d, 出水几乎不含氨氮, 总氮去除率达到 87.6%, 出水总氮浓度为 14.9 $\text{mg}\cdot\text{L}^{-1}$ 。

根据 CANON 反应方程式(1), 若氨氮与亚硝氮全部由厌氧氨氧化途径去除, 则硝氮生成量与总氮去除量之比为 0.11, 因此通常采用出水硝氮增量

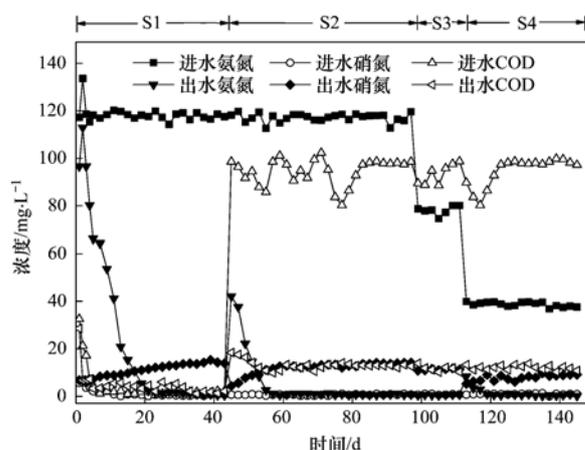


图 2 R1 反应器进出水氮素及 COD 变化

Fig. 2 Nitrogen and COD variations of the R1 reactor

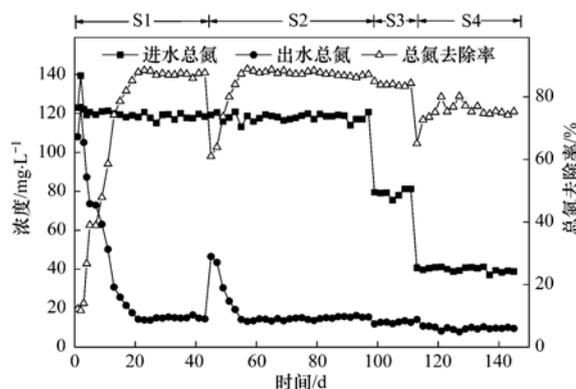
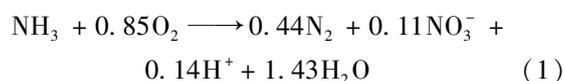


图 3 R1 反应器进出水总氮变化及总氮去除率

Fig. 3 Total nitrogen variation and total nitrogen removal rate of the R1 reactor

和总氮去除量之比表示 CANON 工艺运行情况, 将该值称为特征值。若特征值小于 0.11, 表明出水硝氮减少, 反应器内发生反硝化反应, 若特征值大于 0.11, 是 NOB 活性较强的表现。如图 4 所示为实验期间 R1、R2 反应器特征值变化。



S1 阶段初期, 由于异养菌较多, 特征值为 0.080, 随着异养菌逐渐被淘汰出系统, 特征值逐渐增大。第 23 d 增大至 0.115, 与理论值相近, 随后持续增长。理论值逐渐升高, 可能是由于接种污泥存在部分 NOB, 并且启动初期开始曝气, NOB 无法全部淘汰出反应器。第 35 ~ 45 d, 出水硝氮浓度逐渐稳定, 出水总氮保持在 15.4 $\text{mg}\cdot\text{L}^{-1}$ 左右, 特征值在 44 d 达到 0.127, NOB 活性进一步升高。

为降低出水硝氮浓度, 提高总氮去除率, S2 阶段在 R1 反应器进水中添加 100 $\text{mg}\cdot\text{L}^{-1}$ 丙酸钠富集反硝化菌启动 SNAD 工艺。加入丙酸钠后反硝化活性快速恢复, 第 47 d 出水 COD 浓度小于 20 $\text{mg}\cdot\text{L}^{-1}$, 特征值减小至 0.050, 反硝化与厌氧氨氧

化菌竞争部分亚硝氮, 厌氧氨氧化菌活性降低, 出水硝氮浓度减小至 $5.6 \text{ mg}\cdot\text{L}^{-1}$. 随后厌氧氨氧化菌活性逐渐恢复, 出水硝氮逐渐增加至 $11.9 \text{ mg}\cdot\text{L}^{-1}$, 特征值逐渐升高. 第 59 d 出水氨氮浓度逐步降低至 $1 \text{ mg}\cdot\text{L}^{-1}$ 以下, 总氮浓度达到 88.9%, 出水 COD 浓度小于 $15 \text{ mg}\cdot\text{L}^{-1}$, 平均 COD 去除率为 87.2%, 特征值在 0.11 左右, SNAD 工艺启动成功. 随着反应器的运行, 出水硝氮浓度逐渐升高, 反应器内 DO 浓度依然保持在 $0.4 \text{ mg}\cdot\text{L}^{-1}$, 总氮去除率逐渐下降至 86.9%. 第 87 d 出水硝氮浓度大于 $14 \text{ mg}\cdot\text{L}^{-1}$, 特征值逐渐增大至 0.127, 低温低氨氮环境对 NOB 的抑制作用有限, NOB 活性进一步增长.

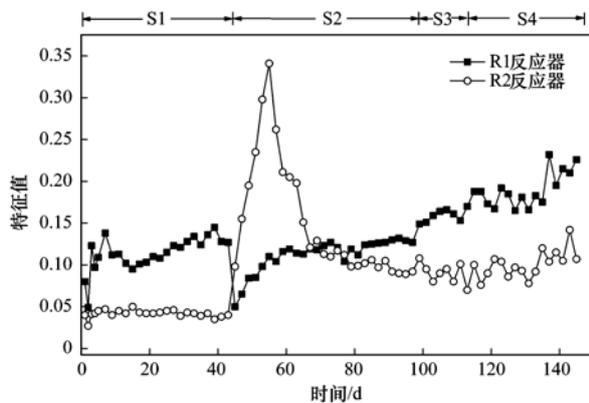
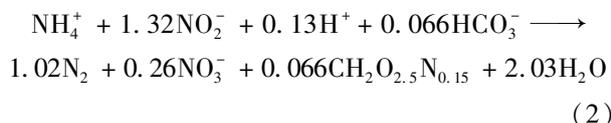


图4 R1、R2 反应器特征值变化

Fig. 4 Characteristic ratio of the two reactors

R2 反应器进出水基质浓度变化如图 5 所示, 反应器进出水总氮变化及总氮去除率如图 6 所示. 反应器启动初期出水氨氮浓度为 $60.7 \text{ mg}\cdot\text{L}^{-1}$, 由于进水中添加 COD, 反硝化作用明显, 出水硝氮浓度仅为 $6.8 \text{ mg}\cdot\text{L}^{-1}$, 特征值为 0.040, 随后 3 d 出水硝氮浓度升高至 $8.7 \text{ mg}\cdot\text{L}^{-1}$. 根据厌氧氨氧化方程式(2)^[7], 厌氧氨氧化菌按 1.32:1 的比例消耗亚硝氮和氨氮基质, 本实验中, 亚硝氮与氨氮消耗比保持在 1.6 左右, 大于理论值 1.32, 说明反硝化菌活性较强, 消耗部分亚硝氮. 随反应器的运行, 氨氮浓度降低至 $43.2 \text{ mg}\cdot\text{L}^{-1}$, 反应器特征值由于出水硝氮的减少而降低至 0.043 左右, SAD 工艺成功启动. 反应器内厌氧氨氧化活性逐渐恢复并保持较高水平, 由于 DO 浓度较低, AOB 没有显示出较高活性.



在 S2 阶段对 R2 反应器进行曝气, 控制 DO 浓度为 $0.5 \text{ mg}\cdot\text{L}^{-1}$, 由于反应器内 DO 浓度升高, 厌氧氨氧化菌活性降低, 出水氨氮浓度增加至 $80.2 \text{ mg}\cdot\text{L}^{-1}$, 反硝化没有受到较大影响, 出水 COD 浓

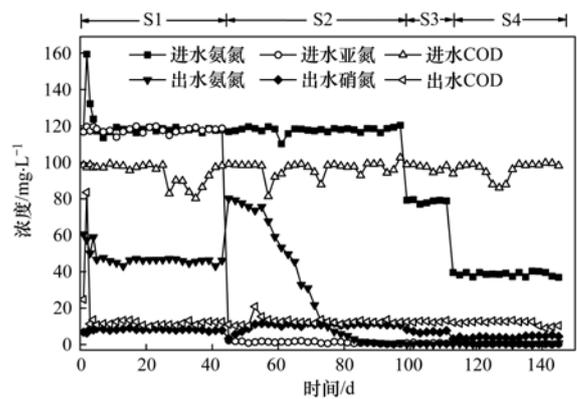


图5 R2 反应器进出水氮素变化

Fig. 5 Nitrogen and COD variations of the R2 reactor

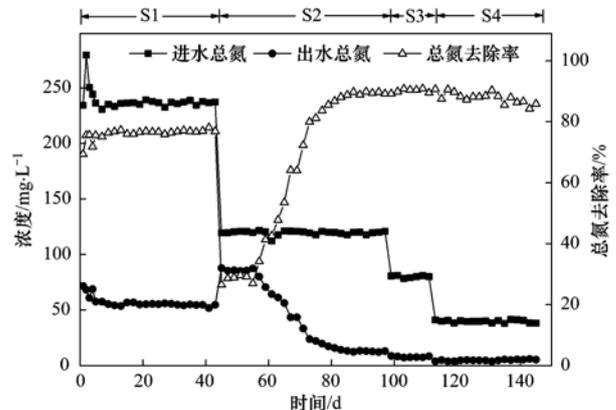


图6 R2 反应器进出水总氮变化及总氮去除率

Fig. 6 Total nitrogen variation and total nitrogen removal rate of the R2 reactor

度在 $15 \text{ mg}\cdot\text{L}^{-1}$ 以下, 保持较低水平. 出水氨氮浓度逐步减少, AOB 活性恢复. 第 75 d, 出水氨氮浓度降低至 $2.0 \text{ mg}\cdot\text{L}^{-1}$, 氨氮去除率达到 98.3%, 出水总氮小于 $15 \text{ mg}\cdot\text{L}^{-1}$, 总氮去除率达到 87.9%, SNAD 工艺启动成功. 随后出水硝氮浓度进一步降低, 最大总氮去除率达到 90.2%, 特征值小于 0.11, 系统运行稳定.

由于启动初期采用厌氧运行, DO 在 $0.5 \text{ mg}\cdot\text{L}^{-1}$ 以下, NOB 难以适应低 DO 环境逐渐被排出系统. 与 R1 反应器相比, R2 反应器的启动及运行过程更加稳定, 没有出现 NOB 过量增殖的现象. 采用先厌氧启动 SAD 工艺的方式可以在启动初期减小 NOB 对反应器稳定性的影响, 为后续曝气启动 SNAD 工艺提供良好的基础.

2.2 低氨氮 SNAD 工艺反应器脱氮性能

S3、S4 为低氨氮浓度运行阶段, 为适应生活污水的低氨氮水质, 将进水氨氮浓度逐渐减少, 探究反应器脱氮性能的变化. S3 阶段将 R1、R2 反应器进水氨氮浓度降低至 $80 \text{ mg}\cdot\text{L}^{-1}$, 运行初期 R1、R2 反应器出水氨氮浓度均处于较低水平, 基本被去除. R1 反应器平均出水硝氮浓度为 $11.1 \text{ mg}\cdot\text{L}^{-1}$,

虽然较 S2 阶段低,但总氮去除率减小至 83.4% 左右,特征值增加至 0.159,NOB 活性进一步提高。Hellenga 等^[22]发现在温度低于 15℃ 时,NOB 的生长速率较高,有利于它们与厌氧氨氧化菌竞争底物亚硝酸盐,导致特征值高于理论值。并且反应器内水温较低,厌氧氨氧化活性较差,NOB 的活性较难抑制,出水硝氮浓度较高。R2 反应器随着进水氨氮浓度的下降,出水硝氮浓度降至 6.5 mg·L⁻¹,出水总氮浓度为 7.5 mg·L⁻¹。运行期间出水总氮浓度保持在 7.4 ~ 8.7 mg·L⁻¹,SNAD 工艺将总氮去除率提高至 90.9%。与 R1 反应器相比,R2 反应器出水总氮浓度较低,并且随进水氨氮浓度降低,特征比增幅较小,总氮去除率较高,NOB 没有出现过量增殖的现象。

S4 阶段将进水氨氮浓度降低至 40 mg·L⁻¹,R1 反应器出水氨氮浓度为 0.6 mg·L⁻¹,出水总氮浓度为 7.7 mg·L⁻¹左右,氨氮去除率最高达 99.7%,平均出水 COD 浓度为 12.6 mg·L⁻¹,总氮去除率降低至 79.3%,特征值增大至 0.212,NOB 活性增强,反应器向全程硝化转变。R2 反应器出水硝氮与总氮浓度进一步降低,出水几乎不含氨氮,平均出水总氮浓度小于 5 mg·L⁻¹,总氮去除率在 85.9% ~ 90.6%,特征值小于 0.126,说明 NOB 活性被抑制在较低水平,在低温低氨氮浓度条件下,R2 反应器更加稳定。

根据以上实验可知,采用先厌氧启动 SAD 工艺可以在前期通过减小 DO 浓度将反应器内 NOB 活性控制在较低水平,将 NOB 逐渐淘洗出系统,为后期曝气启动 SNAD 工艺提供更加稳定的环境,与 R1 反应器相比,R2 反应器出水硝氮浓度更低,小于 6 mg·L⁻¹,总氮去除率大于 88%,在低氨氮浓度条件下没有出现 NOB 过量增殖的情况,并且运行更加稳定,为生活污水低氨氮条件下的稳定运行提供了良好的基础。

2.3 不同启动方式 EPS 及颗粒形态

胞外聚合物(EPS)是微生物在其生长过程中分泌的黏性物质,对污泥颗粒化与颗粒结构的稳定性有较大影响,EPS 主要粘附在细胞壁上,有助于增强微生物对有毒物质的抵抗力,提高微生物对外界环境变化的适应性^[23~25]。其中蛋白质(PN)、多糖(PS)占 EPS 含量的大部分,但对污泥颗粒化的作用有所不同,PN 有利于增强微生物细胞的疏水性^[26],而 PS 可以提高细胞的吸附作用^[27]。PN/PS 可以反映颗粒污泥的稳定性,有研究表明 PN/PS 越高,意味着颗粒污泥沉降性能和稳定性能越好^[28],厌氧氨氧化菌活性越高^[29]。本实验对 SNAD 颗粒

污泥工艺启动及稳定运行期间 PN、PS 及颗粒粒径的变化规律进行了研究。

如图 7、8 所示为 R1、R2 反应器 PN、PS 及 PN/PS 的变化趋势。由于两个反应器启动初期接种的污泥大部分为污水厂污泥,初始污泥中 PS、PN 含量处于较低水平。随反应器运行,微生物活性逐渐升高,PN 与 PS 含量逐渐增长。第 41 d, R1 反应器 PN/PS 为 1.65, R2 反应器达到 2.48。R2 反应器启动初期 PN/PS 增长较快,可能是由于适量的有机物可以促进微生物分泌胞外聚合物^[30],并且反硝化菌的 EPS 可以提高厌氧氨氧化菌活性,促进厌氧氨氧化菌分泌更多 PN^[31]。低氨氮运行阶段, R1 反应器 PN/PS 由 2.76 后逐渐下降至 2.44, R2 反应器 PN/PS 稳定在 2.9 左右。分析其原因,可能是低氨氮运行阶段, R1 反应器中 NOB 过量增殖,厌氧氨氧化菌与 NOB 竞争中处于劣势,厌氧氨氧化菌活性受抑,分泌 PN 量减少,因此污泥 PN/PS 随之降至较低水平。通过 SAD 启动 SNAD 工艺 PN/PS 处于较高水平,厌氧氨氧化菌活性较高,颗粒稳定性和沉淀性能较强。

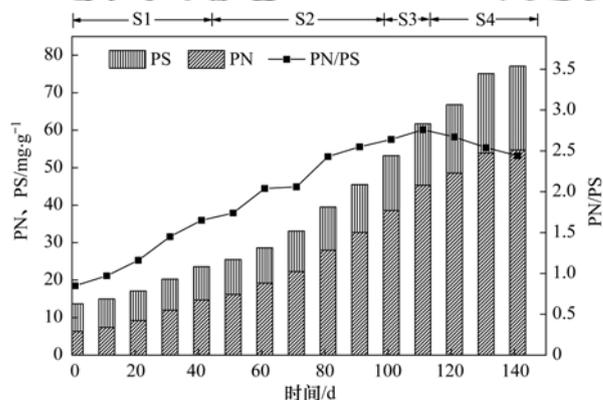


图 7 R1 反应器中 PS 和 PN 含量变化

Fig. 7 Variations of the PS and PN contents in the R1 reactor

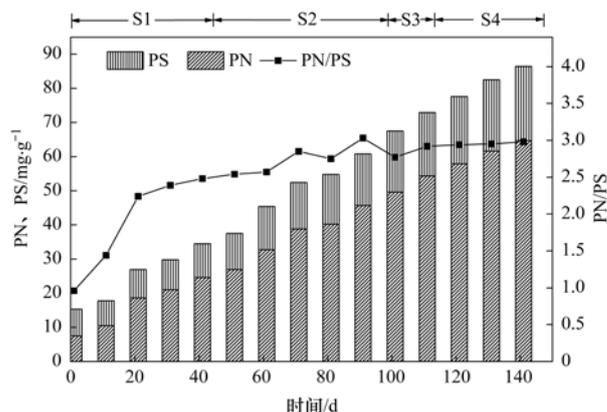


图 8 R2 反应器中 PS 和 PN 含量变化

Fig. 8 Variations of the PS and PN contents in the R2 reactor

S1 阶段初期, R1 反应器和 R2 反应器平均粒

径分别为 152.7 μm 和 145.8 μm (图 9), 基本处于相同水平. S1 阶段末期, R1 和 R2 反应器平均粒径分别为 247.9 μm 和 276.2 μm , R2 反应器平均粒径增长显著, 可能是由于 R2 进水中含有机物. 有研究表明^[32], 适量有机物可以为细菌提供生长所需的营养物质, 促进细胞分泌胞外聚合物, 加快污泥颗粒化. S4 阶段反应器在低氨氮条件下运行, R1 反应器粒径基本保持不变, R2 反应器粒径增长迅速, 分析其原因, 可能是 R1 反应器内部 NOB 过量增殖严重, 破坏了 SNAD 工艺稳定性, 厌氧氨氧化菌活性受抑制. 最终 R1 和 R2 反应器粒径分别为 445.1 μm 和 512.2 μm , 通过 SAD 工艺启动 SNAD 的反应器, 颗粒粒径更大, 粒径增长速率持续保持在 1 $\mu\text{m}\cdot\text{d}^{-1}$, 处于较高水平.

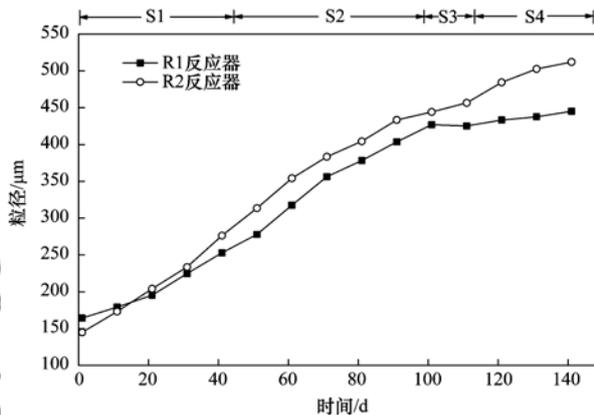


图 9 污泥的平均颗粒粒径

Fig. 9 Mean particle size of the sludge

3 结论

(1) 在低温条件下, 经 SAD 工艺启动的系统, 出水几乎不含氨氮, 总氮去除率在 89.1% 左右. 低氨氮浓度运行时, 最大出水氨氮和总氮浓度分别为 0.9 和 5.7 $\text{mg}\cdot\text{L}^{-1}$, 出水氨氮和总氮浓度达到北京市排放标准一级 A 规定.

(2) 先启动 SAD 工艺可以在启动初期通过厌氧运行将 NOB 逐渐淘汰出系统, 维持了系统的稳定性, 为后续曝气启动 SNAD 工艺提供了良好的基础, 维持了反应器的稳定运行, 实现总氮浓度长期排放达标.

(3) 通过 SAD 工艺启动的反应器内污泥 EPS 含量整体较高, PN 含量达到 64.7 $\text{mg}\cdot\text{g}^{-1}$, PS 含量为 21.7 $\text{mg}\cdot\text{g}^{-1}$, PN/PS 稳定在 2.9 左右, 在低基质浓度下较稳定, 最大颗粒粒径达到 512.2 μm .

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