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低氧污泥丝状菌膨胀的呼吸图谱特征分析

马智博¹, 李志华^{1*}, 杨成建¹, 贺春博², 秋亮¹, 张晶¹

(1. 西安建筑科技大学环境与市政工程学院, 西北水资源与环境生态教育部重点实验室, 西安 710055; 2. 挪威科技大学土木与环境工程系, 特隆赫姆 7050, 挪威)

摘要: 目前对污泥丝状菌膨胀的研究主要关注出水水质和沉降性等特征, 而鲜有关于活性污泥微生物生理状态的报道。针对这一问题, 采用降低 SBR 系统中溶解氧(DO)这一引发污泥丝状菌膨胀的典型条件, 研究了污泥丝状菌膨胀过程中微生物受冲击过程中呼吸图谱与亲和系数的变化。结果表明, 降低 DO 初期, 微生物进入生理适应期, 其特征为活性污泥内源比耗氧呼吸速率($SOUR_e$)突然上升, 自养菌比耗氧呼吸速率($SOUR_n$)大幅下降, 异养菌比耗氧呼吸速率($SOUR_h$)小幅下降后迅速上升, 同时氧亲和系数 K_o 突增; 维持低 DO 时期特征为出水水质和沉降性恶化, 但 $SOUR_n$ 和 $SOUR_e$ 均恢复至较高水平, 且 COD 亲和系数 K_s 和氧亲和系数 K_o 逐步减小, 从理论上证明了低 DO 环境下足够的水力停留时间可以使出水水质更好, 也就说明微生物通过适应性调整可以适应低 DO 环境, 从呼吸代谢和动力学参数的角度验证了“低氧曝气理论”的可行性。研究成果对于污水处理厂节能提供新的理论支持。

关键词: 低溶氧; 丝状菌膨胀; 呼吸图谱; 比耗氧呼吸速率; 亲和系数

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Analysis of Respirogram Characteristics of Filamentous Bulking Caused by Low Dissolved Oxygen

MA Zhi-bo¹, LI Zhi-hua^{1*}, YANG Cheng-jian¹, HE Chun-bo², QIU Liang¹, ZHANG Jing¹

(1. Key Laboratory of Northwest Water Resource, Environment and Ecology, Ministry of Education, School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China; 2. Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim 7050, Norway)

Abstract: The current research on filamentous bulking focuses on the effluent quality and the settling properties but the reports on the microbial physiology under filamentous bulking conditions are seldom. In this study, the variations in the respirogram of microorganisms and affinity coefficient during filamentous bulking were explored in a sequence batch reactor. Low dissolved oxygen, regarded as the typical reason for filamentous bulking, was applied as the stimulation method. The results showed that microorganisms entered the physiological adaptation stage in the early period of low DO. The following properties were observed in the system: ① a sudden increase in the endogenous specific oxygen uptake rate ($SOUR_e$) of activated sludge, ② an abrupt decrease in the specific oxygen uptake rate ($SOUR_n$) of autotrophic bacteria, ③ a rapid increase after a slight decline in the specific oxygen uptake rate ($SOUR_h$) of heterotrophic bacteria and a sudden increase in the oxygen affinity coefficient (K_o). However, maintaining the low DO levels would deteriorate the effluent quality and sedimentation properties, but the $SOUR_n$ and $SOUR_e$ could recover to higher levels after a while and the COD affinity coefficient (K_s) and K_o would decrease gradually. In low DO conditions, a sufficient hydraulic retention time will benefit the effluent quality from a theoretical point of view. Moreover, microorganisms could adapt to low DO conditions, which verifies the feasibility of “low oxygen aeration theory” from the respiration and kinetic parameters. The results from this study provide a theoretical support for energy savings of sewage treatment plant operations.

Key words: low dissolved oxygen; filamentous bulking; respirogram; specific oxygen uptake rate; affinity coefficient

频频发生的污泥膨胀问题成为影响污水处理效率的难题^[1], 因具有频率高、周期长、危害严重及难于控制等特点成为国内外学者研究的焦点。引起污泥膨胀的原因主要有: 低溶解氧(DO)、低温^[2,3]、低污泥负荷(F/M)、营养物缺失、低 pH^[4]等。其中, 低 DO 是诱发污泥膨胀最常见、最典型的因素之一。Insel 等^[5]提出当曝气池中 DO 水平低于 $0.3 \text{ mg} \cdot \text{L}^{-1}$ 时会导致丝状菌的过度繁殖, 暴发严重的丝状菌膨胀, 从而破坏污泥絮体的沉降性能, 甚至引起整个工艺运行的崩溃^[6,7]。

常规的污水处理运行管理是基于对各种水质指标的监测来判断污水处理运行状况, 但在水质恶化的情况下再采取措施控制污泥膨胀为时已晚。微生物呼吸图谱法是基于对微生物呼吸状态的监测而建立的一种污水处理厂运行管理方法^[8], 主要通过测

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作者简介: 马智博(1991~), 男, 硕士研究生, 主要研究方向为废水生物处理理论与技术, E-mail: fukuokaxa@qq.com

* 通信作者, E-mail: lizhihua@xauat.edu.cn

定好氧微生物的耗氧速率 (OUR) 来代表微生物的呼吸速率. 相比传统的以水质指标作为运行管理的主要参考的方法, 微生物对于溶解氧的消耗, 即呼吸速率能够更及时地反映参与污水处理的微生物的实际状态, 因此呼吸速率法得到更多的关注和研究, 且被广泛应用于活性污泥特征分析^[9,10]. 为了表征活性污泥微生物生长动力学的生理适应性, Friedrich 等^[11]提出用最大比生长速率和衰减速率之比来定义活性污泥定量生理状态因子; Pala-Ozkok 等^[12]通过测试 OUR 完成了活性污泥的动力学参数评估; Ergön 等^[13]采用 OUR 评价了不同纳米材料对活性污泥培养基代谢活性及菌群的影响. 李志华等^[14]采用荧光光谱与耗氧速率相结合的方法, 探究了内源呼吸过程中微生物代谢状态变化的典型特征.

若能结合呼吸图谱法对微生物的生理状态活动进行监测, 充分发挥其准确、高效、便捷的优势, 时刻关注活性污泥系统的运行状况, 便可及时有效地采取措施控制引起污泥膨胀的各种因素. 本研究采用呼吸图谱与常规分析相结合的方法, 试图探索和总结活性污泥受到低 DO 冲击时的微生物的变化特征, 从出水水质、沉降性、污泥浓度、呼吸图谱、动力学参数等方面分析污泥微生物在低 DO 冲击时生理变化特征, 研究低 DO 条件下微生物的适应状况.

1 材料与方法

1.1 实验装置

实验装置为有机玻璃制成的 SBR 反应器, 外加水浴套筒使其温度控制在 $(20 \pm 1)^\circ\text{C}$. 通过 PLC 控制曝气泵、搅拌器、电磁阀等, 进水采用潜水泵结合液位继电器控制, 整个实验装置实现自动控制. 反应器有效容积为 10 L, 每次进水 4 L. 每个周期 6 h, 其中进水 4 min, 曝气搅拌 184 min, 沉淀 58 min, 出水 4 min. 通过调整曝气强度来控制 DO 水平, pH 维持在 7.0 ~ 8.0.

1.2 进水水质及接种污泥

进水采用人工配水的方式, 以 NaAc 为碳源, NH_4Cl 为氮源, KH_2PO_4 为磷源. 进水 COD 为 $600 \sim 750 \text{ mg} \cdot \text{L}^{-1}$, $\text{NH}_4^+ - \text{N}$ $60 \sim 70 \text{ mg} \cdot \text{L}^{-1}$, $\text{PO}_4^{3-} - \text{P}$ $6 \sim 8 \text{ mg} \cdot \text{L}^{-1}$, 微量元素为 $0.4 \text{ mL} \cdot \text{L}^{-1}$. 微量元素组成为: $0.15 \text{ g} \cdot \text{L}^{-1} \text{ H}_3\text{BO}_3$, $0.03 \text{ g} \cdot \text{L}^{-1} \text{ CuSO}_4 \cdot 5\text{H}_2\text{O}$, $0.18 \text{ g} \cdot \text{L}^{-1} \text{ KI}$, $0.12 \text{ g} \cdot \text{L}^{-1} \text{ MnCl}_2 \cdot 4\text{H}_2\text{O}$, $0.06 \text{ g} \cdot \text{L}^{-1} \text{ Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$, $0.12 \text{ g} \cdot \text{L}^{-1} \text{ ZnSO}_4 \cdot 7\text{H}_2\text{O}$, $0.15 \text{ g} \cdot \text{L}^{-1} \text{ CoCl}_2 \cdot 6\text{H}_2\text{O}$, $1.54 \text{ g} \cdot \text{L}^{-1} \text{ FeSO}_4 \cdot 7\text{H}_2\text{O}$,

$12.74 \text{ g} \cdot \text{L}^{-1} \text{ EDTA}$. 反应器接种污泥取自某市政污水处理厂倒置 A^2/O 工艺曝气池末端回流污泥, MLSS 为 $4000 \text{ mg} \cdot \text{L}^{-1}$ 左右.

1.3 低 DO 冲击实验

培养过程中, 严格控制温度、进水基质、pH、营养物等易造成污泥膨胀的因素. 仅通过控制曝气强度调整曝气阶段的 DO 水平, 保证冲击时 DO 水平低于 $0.5 \text{ mg} \cdot \text{L}^{-1}$, 其他条件基本维持不变.

1.4 分析方法

反应器中 DO 和 pH 由 HQ40d 便携式 DO 仪 (HACH, 美国) 测定, COD、 $\text{NH}_4^+ - \text{N}$ 、 $\text{NO}_3^- - \text{N}$ 、 $\text{NO}_2^- - \text{N}$ 、总磷、MLSS 和 SVI 按标准方法测定^[15]. 污泥密度通过蔗糖密度浓度对比法测定. 污泥形态观察在 Nikon 90i (Nikon, 日本) 显微镜下进行.

微生物呼吸图谱包含总呼吸速率 (OUR_{enc})、内源呼吸速率 (OUR_e)、自养菌呼吸速率 (OUR_n)、异养菌呼吸速率 (OUR_c) 这 4 个参数, 其中 $\text{OUR}_{\text{enc}} = \text{OUR}_e + \text{OUR}_n$, $\text{OUR}_{\text{enc}} = \text{OUR}_e + \text{OUR}_n + \text{OUR}_c$. 呼吸图谱各项参数通过智慧工作站 (WBM450, 西安绿标水环境科技有限公司) 测试得到. 其测试包含以下步骤: ①加入 0.3 L 的活性污泥和 0.9 L 的清水于密闭恒温好氧反应器, 加入 PBS 缓冲溶液洗泥 3 次并曝气 2 h; ②开启曝气泵曝气, 使反应器中溶解氧 (DO) 上升到 $7 \text{ mg} \cdot \text{L}^{-1}$, 关闭曝气泵, 开始均匀搅拌, 然后监测搅拌过程中的 DO 下降过程, 通过直线拟合得到其斜率 (即 OUR 值) 为 OUR_e ; ③加入预定量的氮源 (NH_4Cl), 重复步骤②可得 OUR_{enc} ; ④加入预定量的碳源 (NaAc), 再重复步骤②可得到 OUR_{enc} . OUR_n 和 OUR_c 通过 4 个参数之间的关系换算得到. 整个测试过程中通过在线监测 pH 和温度, 开启加药系统加入 HCl 或 NaOH 调整 pH. 为消除污泥浓度对呼吸速率的影响, 本实验采用比耗氧呼吸速率 (SOUR) 表示微生物的呼吸特性, 其中 $\text{SOUR} = \text{OUR}/\text{MLSS}$. COD 亲和系数 K_s 、溶解氧亲和系数 K_o 通过测定耗氧速率, 然后拟合计算得到, 测定方法见文献[16,17].

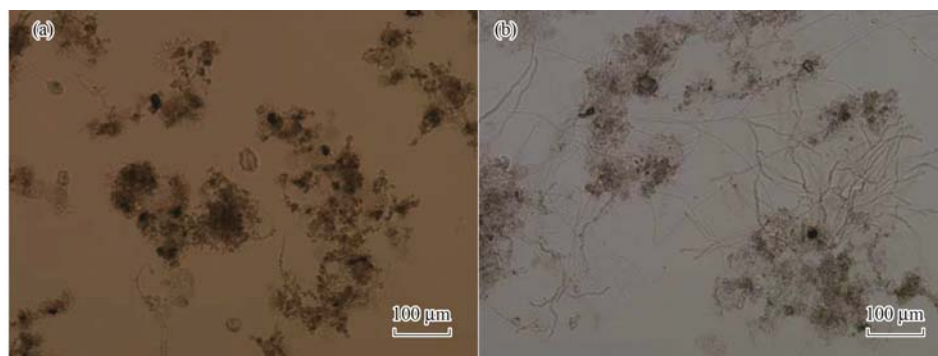
2 结果与讨论

2.1 低 DO 冲击过程中污泥沉降性与出水水质变化

污泥接种初期溶解氧维持在 $2 \sim 4 \text{ mg} \cdot \text{L}^{-1}$, 反应器内污泥浓度小幅增长后趋于平稳, SVI 维持在一个相对较稳定的水平. 由于接种污泥本身存在一定程度的膨胀, 反应器运行初期 SVI 为 $200 \text{ mL} \cdot \text{g}^{-1}$ 左右. 为了实现污泥膨胀, 从反应器接种后的第 6 d

起,限制曝气,溶解氧维持在 $0 \sim 0.5 \text{ mg} \cdot \text{L}^{-1}$,由于丝状菌与菌胶团菌在 DO 的竞争处于优势地位,从而大量滋生,引起丝状菌膨胀(如图 1)。如图 2

所示,当 DO 降低时,SVI 迅速升高,从 $200 \text{ mL} \cdot \text{g}^{-1}$ 左右上升至 $400 \text{ mL} \cdot \text{g}^{-1}$,污泥大量流失,MLSS 从 $4000 \text{ mg} \cdot \text{L}^{-1}$ 左右逐渐降低至 $2000 \text{ mg} \cdot \text{L}^{-1}$ 左右。



(a)为降低 DO 前,(b)为降低 DO 后;图中标尺长度均为 $100 \mu\text{m}$

图 1 污泥形貌特征

Fig. 1 Morphology of sludge

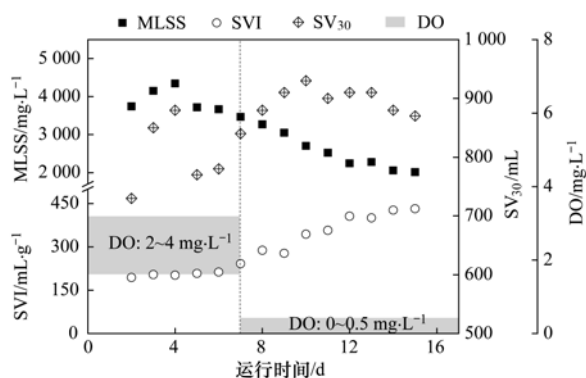


图 2 低 DO 冲击过程中沉淀性能的变化特征

Fig. 2 Settling properties of the low oxygen process

由于去除有机物、硝化作用以及生物吸磷过程都需要在好氧状态下进行,而低 DO 会引起相关功能菌的活性受到抑制。从图 3 可知,降低 DO 后,出水水质(COD、 $\text{NH}_4^+ - \text{N}$ 、总磷等)均先后出现恶化,COD 去除率从 90% 降至 40% 左右, $\text{NH}_4^+ - \text{N}$ 去除率降至 10% 以下。整个恶化过程中出水水质按超标时间排序为: $\text{NH}_4^+ - \text{N}$ > 总磷 > COD。出水 $\text{NO}_3^- - \text{N}$ 则一直处于较低水平,其原因是低 DO 环境能够使反硝化更好地完成。Guo 等^[18]研究表明,低 DO 会导致微生物活性变弱,降低微生物的脱碳除氮能力。同时,Fan 等^[19]也提出低 DO 可能会导致活性污泥絮体的不完全硝化,并且伴随沉降性的恶化。本实验也得到类似的结论。同时由于好氧阶段 DO 水平较低,聚磷菌的好氧吸磷受到影响,反而为厌氧释磷提供了条件,导致出水中总磷高于进水。

2.2 低 DO 冲击过程中呼吸图谱变化特征分析

呼吸作用是微生物的固有特征,通过测试呼吸速率的变化可以得到微生物新陈代谢活动中的重要

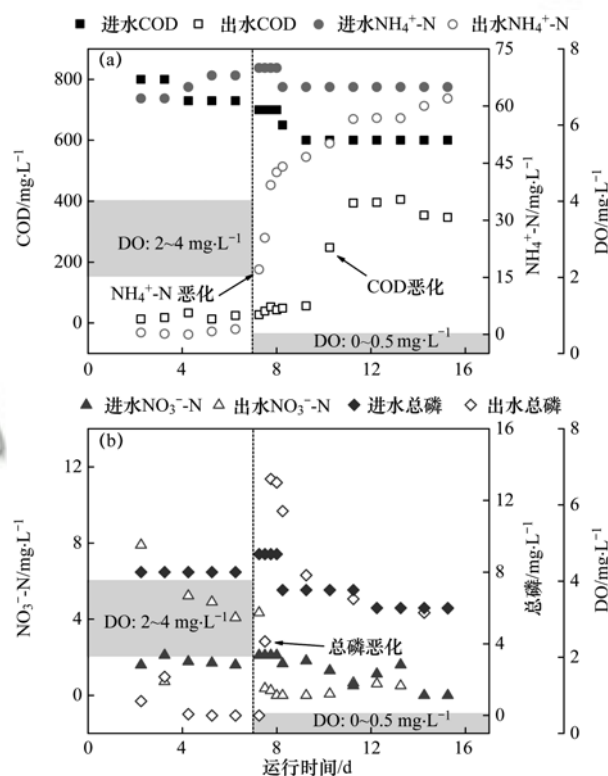


图 3 低 DO 冲击过程中出水水质的变化特征

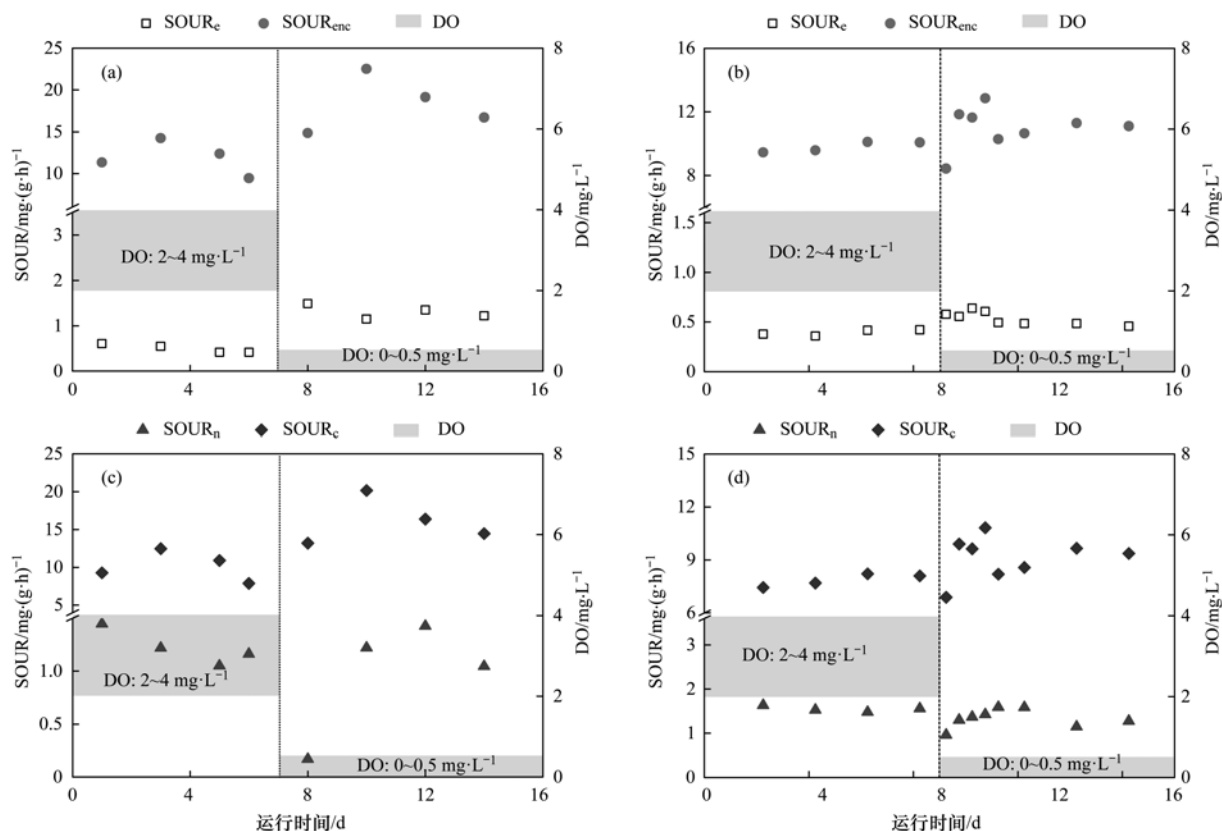
Fig. 3 Variation in effluent quality in the low oxygen process

信息,从而分析微生物对外界环境改变做出的适应性反应。如图 4 所示,降低 DO 前后,呼吸图谱的各项指标均发生改变。 SOUR_e (以 O_2/SS 计,下同)出现了突增[图 4(a)],从 $(0.496 \pm 0.098) \text{ mg} \cdot (\text{g} \cdot \text{h})^{-1}$ 上升至 $1.488 \text{ mg} \cdot (\text{g} \cdot \text{h})^{-1}$,为原来的 3 倍左右,之后稳定在 $(1.241 \pm 0.101) \text{ mg} \cdot (\text{g} \cdot \text{h})^{-1}$ 。本实验监测到低 DO 冲击条件下内源比耗氧呼吸速率发生突增,为确认上述结果准确性,设置上述实验

的验证实验,其实验条件与第一次完全相同. 从验证实验结果来看,降低 DO 时, $SOUR_e$ 变化趋势[图 4(c)]与第一次相同. 与此类似的是,当温度升高时, $SOUR_e$ 也会上升^[20];李志华等^[21]研究表明,投加 NaClO 控制污泥膨胀时,活性污泥 OUR_e 与内源呼吸比(OUR_e/OUR_i)也发生了突增. 因此,内源呼吸速率的上升可以表征微生物是否受到外界环境的冲击.

在降低 DO 时[图 4(b)], $SOUR_n$ 从 $(1.219 \pm 0.167) \text{ mg} \cdot (\text{g} \cdot \text{h})^{-1}$ 立即下降至 $0.168 \text{ mg} \cdot (\text{g} \cdot \text{h})^{-1}$, 之后又逐渐恢复至 $(1.231 \pm 0.190) \text{ mg} \cdot (\text{g} \cdot \text{h})^{-1}$. 而

$SOUR_e$ 在降低 DO 后呈上升趋势,且在运行第 10 d 上升至最大,之后逐渐恢复. 由于异养菌在活性污泥中所占比例较高,因此 $SOUR_{enc}$ 变化趋势与 $SOUR_e$ 相同. 同时验证实验的结果也显示了[图 4(d)], $SOUR_n$ 受到低 DO 冲击时立即下降,之后又逐渐恢复这一趋势. 而不同的是,验证实验监测到低 DO 冲击时 $SOUR_e$ 也存在下降的过程,只是出现时间较短,以致于第一次低 DO 冲击时未监测到. $SOUR_e$ 的快速下降并恢复恰好说明异养菌对环境的改变有更强的适应能力^[22,23]. 这与本文前面所述的出水 NH_4^+-N 最早发生超标现象的结论一致.



(a)、(b)为第一次低 DO 冲击实验,(c)、(d)为验证上述实验数据

图 4 低 DO 冲击过程中呼吸图谱的变化特征

Fig. 4 Variation of respirogram in the low oxygen process

此外,在改变 DO 的初期, $SOUR_e$ 突然上升,同时 $SOUR_n$ 突然下降,这可能是微生物受到外界环境改变时的一种应激反应,微生物种群发生了生理适应性调整^[24]. 而维持低 DO 环境,两者呼吸速率又能逐渐恢复,说明此时功能性菌群可以适应低 DO 环境,仍然保持了较好的代谢潜能. 这与 Park 等^[25]提出的氨氧化菌能够适应低 DO 环境,并在 DO 浓度为 $0.12 \text{ mg} \cdot \text{L}^{-1}$ 时完成良好的硝化结论一致. 而此时出水 COD 和 NH_4^+-N 仍然超标,其原因是活性污泥系统中缺乏足够 DO 且水力停留时间较短,无法

为功能性菌群提供新陈代谢的必要条件,从而影响微生物的生命活动. 同时,彭赵旭等^[26]提出,在好氧水力停留时间充分的条件下,低氧环境不但不会影响丝状菌微膨胀污泥的硝化进程,而且还有助于同步硝化反硝化.

2.3 低 DO 冲击过程中动力学参数变化特征分析

从图 5 可以看出,在降低 DO 之前,异养菌的氧亲和系数 K_0 为 $(0.096 \pm 0.013) \text{ mg} \cdot \text{L}^{-1}$, 基本保持稳定,当 DO 开始降低时, K_0 突增至 $0.134 \text{ mg} \cdot \text{L}^{-1}$, 随着时间的延长,又迅速下降至 (0.073 ± 0.005)

$\text{mg}\cdot\text{L}^{-1}$,且低于降低 DO 之前. K_0 的突然增大,说明微生物在降低 DO 时,微生物维持较高呼吸速率需要更高浓度的 DO,而实际无法满足条件,此时微生物呼吸速率可能会受到影响[图 4(b)、4(d)],但是自养菌与异养菌受影响程度不同,其原因可能是低 DO 条件下,异养菌比自养菌有更强的争夺氧气的能力^[27],这也是出水中 NH_4^+-N 比 COD 恶化时间早的原因,也进一步说明,异养菌比自养菌有更强的适应环境的能力^[22,23]. 同时, K_0 的突然增大后减小,也充分证实了微生物在降低 DO 初期经历了生理适应性调整期. 当维持低 DO 水平培养时, K_0 逐渐减小趋于稳定,说明微生物经过生理适应性调整,逐渐适应低 DO 环境,正如图 4(b)所示,其功能性菌群呼吸速率也会逐渐恢复.

活性污泥 COD 亲和系数 K_s 在降低 DO 后逐渐降低,说明活性污泥在低 DO 环境下维持较高代谢活性时所需的 COD 浓度降低. 对比观察污泥形貌特征(如图 1),低 DO 环境下污泥发生了一定程度的丝状菌膨胀,污泥絮体更加松散,且丝状菌大量伸出絮体外. 相比絮体形成菌,在低 DO 条件下丝状菌的基质亲和系数更低^[28],且在低基质浓度下能够保持较高的生长速率. 低 DO 环境下,活性污泥保持了较低的氧亲和系数和 COD 亲和系数,意味着膨胀污泥能够在 DO 不足时依然保持较强的生理特性,在水力停留时间足够时,理论上可以使出水 COD 更低. 这就从动力学参数的角度验证了“低 DO 丝状菌污泥微膨胀节能理论”的可行性^[29,6].

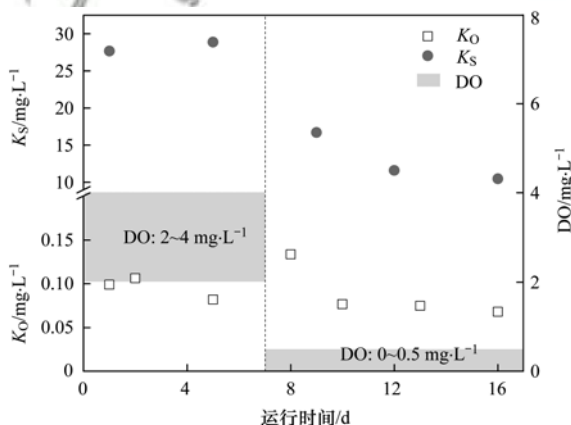


图5 低 DO 冲击过程中异养菌亲和系数和污泥密度的变化特征

Fig. 5 Variations in the affinity coefficient and sludge density in the low oxygen process

3 结论

(1)当 DO 降低时,污泥内源比耗氧呼吸速率突然增大,因此其上升可作为污泥微生物受到低 DO

冲击的标志.

(2)长时间的低 DO 环境会造成出水水质和沉降性能的恶化,但是在低 DO 水平下自养菌和异养菌依然能保持较好的代谢潜能,而造成出水水质恶化原因是溶解氧供给不足,导致反应速率下降,从而需要更长的水力停留时间. 因此在实际工程中,如果短期无法提供足够的 DO,可以通过延长水力停留时间来保证出水水质达标.

(3)低 DO 冲击时,活性污泥微生物会进入生理适应期,其特征为内源呼吸速率上升,自养菌呼吸速率迅速下降,氧的亲和系数快速上升. 长时间的低 DO 环境,会使 K_0 和 K_s 逐渐减小,从呼吸代谢和动力学参数的角度验证了“低氧曝气理论”的可行性.

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