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Reducing aeration energy consumption in a large-scale membrane bioreactor: Process simulation and engineering application

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ABSTRACT

Reducing the energy consumption of membrane bioreactors (MBRs) is highly important for their wider application in wastewater treatment engineering. Of particular significance is reducing aeration in aerobic tanks to reduce the overall energy consumption. This study proposed an in situ ammonia-N-based feedback control strategy for aeration in aerobic tanks; this was tested via model simulation and through a large-scale (50,000 m^3/d) engineering application. A full-scale MBR model was developed based on the activated sludge model (ASM) and was calibrated to the actual MBR. The aeration control strategy took the form of a two-step cascaded proportion-integration (PI) feedback algorithm. Algorithmic parameters were optimized via model simulation. The strategy achieved real-time adjustment of aeration amounts based on feedback from effluent quality (i.e., ammonia-N). The effectiveness of the strategy was evaluated through both the model platform and the full-scale engineering application. In the former, the aeration flow rate was reduced by 15–20%. In the engineering application, the aeration flow rate was reduced by 20%, and overall specific energy consumption correspondingly reduced by 4% to 0.45 kWh/m^3-effluent, using the present practice of regulating the angle of guide vanes of fixed-frequency blowers. Potential energy savings are expected to be higher for MBRs with variable-frequency blowers. This study indicated that the ammonia-N-based aeration control strategy holds promise for application in full-scale MBRs.

1. Introduction

Membrane bioreactors (MBRs) have been widely used for wastewater treatment and reclamation engineering over the past decade (Huang et al., 2010; Judd and Judd, 2011; Xiao et al., 2014). Compared with conventional activated sludge (CAS) processes, MBRs possesses advantages such as high effluent quality and low sludge production, and provide promising alternatives in areas facing water crises and needing to meet stringent pollutant discharge standards. However, the operational cost of MBRs, especially related to energy consumption, has typically been greater than that of CAS systems (Judd and Judd, 2011). The majority of energy is consumed for aeration, both in biological tanks for pollutant degradation, and in membrane tanks for retarding membrane fouling (Brepols et al., 2010; Yan et al., 2015). The energy consumption of aeration accounts for 70–80% of total consumption of the wastewater treatment process. A total of 40–60% of aeration energy is consumed in biological tanks (Xiao et al., 2014). The optimization of aeration in MBRs is therefore of practical importance to reduce operational costs and increase the competitiveness of MBRs.

The optimization of aeration could be achieved via regulation of blowers, including by altering the angle of the guide vanes for fixed-frequency blowers and by altering the frequency of the alternating current for variable-frequency blowers. Aeration can be controlled manually or automatically, on the basis of process parameters, e.g., mixed liquor suspended solids (MLSS) concentrations (Zha et al., 2006), dissolved oxygen (DO) concentrations

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(Ingildsen et al., 2002), and oxidation-reduction potential (ORP) (Fatone et al., 2008). Among these, DO-based automatic aeration control has attracted most attention in both simulations and experimental validations aiming to reduce energy consumption (Gabarron et al., 2015; Ingildsen et al., 2002; Pittoors et al., 2014; Wang et al., 2007). DO-based aeration control aims to maintain a stable DO concentration in biological tanks. Energy consumption reduction and better nutrient removal performance can be achieved by optimizing the DO setpoint of the control (Gabarron et al., 2015). However, DO is merely an intermediate variable between aeration and effluent quality. The determination of optimal aeration demand is a trade-off between aeration amount and effluent quality. Moreover, maintaining DO concentrations at a so-called "optimal" level during operations could still lead to real-time fluctuations in effluent quality under dynamic influent conditions, meaning that aeration is never fully optimized. Given the above, a feedback control mechanism that has its starting point in effluent quality (rather than DO) might have greater potential for aeration optimization and hence energy saving.

Model tools are essential for automatic feedback control, which is expected to enable real-time determination of aeration demand according to effluent quality. Establishment of a quantitative relationship between effluent quality and aeration is of paramount importance. The relationship should itself be precise and simple enough for calculation that allows real-time control. However, the well-known activated sludge model (ASM), which has been broadly used for describing the wastewater treatment process (Hauduc et al., 2013), consists of multiple differential formulas (Henze et al., 1999). The solving process is complicated, making it difficult to meet real-time control requirements. If a straightforward empirical relationship, which is simple in terms of calculation but matches well with the complete ASM, could be extracted from the latter, this would be of great benefit for real-time feedback control in practical wastewater treatment systems.

When describing the wastewater treatment process of MBRs via the ASM, the following considerations are particularly important. First, membrane rejection prolongs solid retention time (SRT) and lowers the food-to-microorganisms (F/M) ratio in MBR, resulting in significant differences in kinetic parameters between MBR and CAS (Fenu et al., 2010). Second, near-saturated DO concentrations are achieved in membrane tanks due to abundant aeration for membrane scouring (Sun et al., 2014). The DO-enriched mixed liquor of the membrane tank is usually recirculated back to the aerobic zone of the biological tanks, which can render the oxygen balance between MBR and CAS systems quite different (Sun et al., 2015).

This study aimed to reduce aeration energy consumption in a large-scale MBR via process simulation and engineering application. First, an MBR-adapted ASM model was calibrated to achieve an acceptable simulation of the full-scale MBR. Second, an effluent-quality-based feedback control strategy for aeration in biological tanks was established, comprising a two-step cascaded proportion-integration (PI) control process; this involved establishing a simple mathematical relationship between aeration and effluent quality, which was also accordance with the ASM. The strategy calculated a dynamic DO setpoint according to in situ ammonia-N concentrations, then calculating a dynamic aeration flow rate for adjusting the blowers. The algorithmic parameters were optimized via tentative model simulation. Third, this strategy with optimized parameters was applied to practical operation of a large-scale MBR, to validate the feasibility of the control strategy. Energy saving potential was assessed via model simulation, and actual effectiveness was further examined via practical application, by comparing energy levels and in situ ammonia-N concentrations before and after application of the aeration control strategy.

2. Material and methods

2.1. Full-scale MBR

The full-scale MBR was installed in a municipal wastewater treatment plant (WWTP). The WWTP, with a capacity of 50,000 m^3/d, was located in Wuxi (30°36′ N, 120°19′ E, Jiangsu Province, south of China) and treated a cocktail of domestic and industrial wastewaters. The MBR process was operated at hydraulic and solid retention times of 13 h and 15 d, respectively. The hollow fiber membrane in use was of hydrophilic polyvinylidene fluoride (PVDF), with a nominal pore size of 0.2 μm, and was supplied by OriginWater (China).

The overall process consisted of four parallel identical series, with the process flow of each schematically shown in Fig. 1. In situ DO and ammonia-N probes (E+H, Switzerland) were placed at the ends of aerobic tanks. Concentrations of DO and ammonia-N were monitored via selective electrode analysis. An electromagnetic flow meter (E+H, Switzerland) was placed at the influent pump to monitor the flow rate.

Three high-speed centrifugal blowers (GL-TURBO, China) were installed for aeration in aerobic tanks. Each blower could provide a maximum aeration flow rate of 4800 m^3/h at a pressure of 68.6 kPa. The nominal power of each blower was 132 kW. Output aeration flow rate could be adjusted by changing the opening angle of the guide vane, achieving an aeration range of 60–100% of maximum flow rate. The blowers were operated with one in service and two on standby at high temperatures, and with two in service and one on standby at low temperatures, as determined by the operators of the WWTP.

2.2. Software for modeling and simulation

The Activated Sludge Model 2d (ASM2d) was used to simulate the municipal wastewater treatment process due to its suitable description of carbon oxidation, nitrification, denitrification, biological and chemical phosphorus removal, and denitrification by PAOs (Henze et al., 1999). Biowin software (Envirosim Corp., Canada), based on ASM2d, was used as the simulation platform in this study. The membrane unit was described as a biological tank with additional parameters of membrane rejection. The rejection rate of membrane for particles and colloids was set as default values (100% and 95%, respectively) in this study. The software consisted of simulation and control modules. Steady-state and dynamic-state simulation could be achieved in the simulation module. Various control strategies (e.g., on/off, step, and PI/PID) could be operated along with the process simulation.

2.3. Establishment of the full-scale MBR model

The biological treatment process consisted of four parallel series, each of which included an anoxic tank (A_2), an anaerobic tank (A_1), an interchangeable A/O tank (X), an aerobic tank (O), and membrane tanks (M). The treatment capacity of each series was 12,500 m^3/d (Fig. S1). Each tank was modeled according to its length, width, and height. Sludge recirculation ratios were set according to actual operational conditions (500% from M to O, 100% from O to A_2, and 200% from O to X). A_2 and A_1 were set up with no aeration (DO = 0 mg/L). X and O were set up with constant-flow aeration. The total aeration flow rate was set at 2400 m^3/h (in winter) and 1200 m^3/h (in summer), according to the actual operation of blowers. The aeration distribution ratio of X to O was 0.15:0.85.