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Optimization of aeration profiles in the activated sludge process

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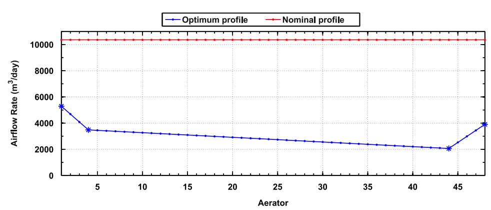
HIGHLIGHTS

- Aeration rate in activated sludge process is optimized via model of a real plant.
- Aeration can be reduced by 60% or more with non-uniform airflow distribution.
- Similar savings can be achieved with segments of equally aerated zones in the tank.
- Effluent quality can be preserved even during storms if a safety factor is employed.
- Performance of reduced-aeration profiles is studied with dynamic storm simulations.

GRAPHICAL ABSTRACT



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ABSTRACT

We show that the aeration rate in the activated sludge process, which is responsible for the greatest energy burden (up to 50%) in wastewater treatment, can be reduced by more than 60%, while preserving an effluent quality of less than 0.10 mg/L of ammonia and more than 8.5 mg/L of dissolved oxygen. An in-depth survey of the performances of different aeration profiles is given through utilization of an activated sludge tank model that was calibrated and validated with data from a real plant. First, the total rate of aeration is manipulated while employing equal rates of local aeration across the activated sludge tank. Then, scenarios with a nonuniform distribution of local aeration rates are investigated. For this purpose, a mixed-integer nonlinear programming (MINLP) problem was devised to minimize computational burden, which was solved using a genetic algorithm. Also, a similar MINLP problem was set to obtain aeration profiles with segments of equally aerated zones in the tank, which can facilitate execution in real plants. Finally, all aeration profiles were challenged with a 2-day storm through dynamic simulations.

1. Introduction

The energy expense of aeration process in activated sludge tanks has long been a major topic in wastewater treatment research. Owing to the presence of multiple biological species that form the activated sludge, the activated sludge process requires continuous aeration of the mixed liquor to supply these microorganisms with sufficient dissolved oxygen, which enables the conversion of larger organic molecules in wastewater into smaller ones. In addition to its biological role, the forced aeration allows sufficient mixing in the activated sludge tank and contributes to the overall efficiency of the treatment process.

The consequences of insufficient aeration are typically encountered in the tank effluent as low dissolved oxygen and high ammonia concentrations, and usually lead to the violation of discharge permits

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enforced by local authorities. Typical discharge permits for the effluent quality of water reclamation plants (WRPs) are given in Table 1, as specified by the National Pollution Discharge Elimination System (NPDES). It should be noted that the effluent concentrations of WRPs are typically kept much lower than the values presented in Table 1. For the plant investigated in this study, which is introduced in the next section, the effluent ammonia concentration is usually less than 0.10 mg/L, while the dissolved oxygen concentration is kept well above 6 mg/L under nominal operating conditions.

These values may seem to suggest that the wastewater treatment operation is carried out with high efficiency. On the other hand, very high aeration rates are utilized in order to maintain such an effluent quality, and this results in a big energy burden associated with the compression of air. Several sources report that about 40–60% of the energy expenditure of a WRP is associated with the aeration process (Daw et al., 2012; Ganesan, 2013; Owen, 1982; Rieger et al., 2012; Spellman, 2008). In a recent study, we have shown that these aeration rates were in excess and could be decreased by 50% on average with minimal effect on the effluent quality (Ozturk and Teymour, 2014). As such, there are various studies on the minimization of the aeration in the activated sludge process with different process configurations, which usually include a control approach as well. For example, Chachuat et al. (2000, 2005) use a dynamic optimization approach to determine the optimal sequence of on/off periods for a small size alternating activated sludge (AAS) process. Fikar et al. (2005) employ a similar approach to the same process and account for the effect of diurnal variation in influent flow rate and composition. Åmand and Carlsson (2012) utilize feedback control and optimization on a single-compartment process model, and discuss control strategies for plants where effluent constraints are defined over months or years. Piotrowski et al. (2008) consider an activated sludge tank consisting of one anaerobic, one anoxic, and four aerobic zones and use a model predictive control approach within a hierarchical control framework.

Despite these efforts, application of advanced control strategies in WWTPs is very limited globally, due to the high complexity of the process and the cost of capital investment required (Weijers, 2000; Ingildsen, 2002; Hill et al., 2002; Jeppsson et al., 2002). In addition, there is skepticism against optimization of aeration in the activated sludge processes, which usually stems from the sensitivity of effluent quality to aeration and the necessity to protect against permit violations. In the absence of a clear insight toward the relation of process conditions and the required rate of aeration, it is usually preferred to keep the total aeration rates higher than necessary to avoid the effects of upstream disturbances, such as storms, temperature changes, or the quality and quantity of the influent wastewater.

Consequently, WWTPs need simpler approaches in the preliminary stages of minimization of aeration, which would ideally be performed with minimal investment and effort. Our work provides an option for such plants to conduct an offline optimization, which would yield an aeration profile that can be modified slightly to suit various conditions in the absence of automatic control. For this purpose, we use a realistic, validated aeration tank model, which consists of 48 aeration zones (modeled as CSTRs) and a settling tank, and employ an optimization approach to calculate optimal aeration profiles that would minimize the air usage and preserve the effluent quality. Considering the potential limitations for application, such as lack of automatic control valves for adjusting individual zones, we propose aeration profiles consisting of (i) uniform increase and decreases across the activated sludge tank, (ii) multiple uniformly aerated zones (*i.e.* steps) that allow easy manipulation of the profile using a few header valves. In addition, we investigate the offline use of these profiles under excessive storm events to demonstrate their feasibility.

Table 1
National Pollution Discharge Elimination System (NPDES) permits on plant effluent.[a]

Pollutant	Discharge permit (mg/L)
BOD_5	4–30 mg/L (monthly average)
Suspended solids	5–30 mg/L (monthly average)
NH_3–N	2.5 mg/L (monthly average, April to October)
	5.0 mg/L (daily limit, April to October)
	4.0 mg/L (monthly average, November to March)
	8.0 mg/L (daily limit, November to March)

[a] Environmental Regulations for the State of Illinois (http://www.ipcb.state.il.us/SLR/IPCBandIEPAEnvironmentalRegulations-Title35.aspx).

In our previous work (Ozturk and Teymour, 2014), we have used bifurcation theory to investigate the steady state behavior of the process for different aeration rates and wastewater temperatures. However, this analysis was carried out with an aeration profile, in which the airflow rates were kept the same in all aerators across the tank, while the total airflow rate was manipulated. In this work, we show that it is possible to further minimize the total aeration rate of an activated sludge tank through utilization of a nonuniform distribution of local airflow rates, and an activated sludge tank model that was calibrated and validated with about 8 years of plant data from Stickney WRP, in Chicago, IL. Serving a population equivalent of 10.1 million and a capacity of 1.4 billion gallons per day (BGD), Stickney WRP is currently the largest WWTP in the world. The plant operates with strict daily and monthly effluent regulations, and the effluent dissolved oxygen is kept around 8.5 mg/L on average, thus making the optimization task more challenging, but also essential.

In the rest of this study, we first show that the aeration can be greatly reduced by adjusting the total rate of aeration, while keeping local aeration rates across the tank equal. Next, we allow different aeration rates across the tank and devise a mixed-integer nonlinear programming (MINLP) problem, which was solved using a genetic algorithm (GA) to show that further reduction in aeration is possible. Then, we test the robustness of the optimized aeration profiles toward excessive storm events. Finally, we demonstrate that simple structured (segmented) aeration profiles can be easily utilized in most WRPs for aeration minimization efforts without the need for automatic control valves.

2. Water reclamation plant and model

2.1. Stickney water reclamation plant

Throughout this study, we focus on the activated sludge tanks of the Stickney water reclamation plant, which is located in west of Chicago, IL. The design capacity of Stickney WRP is 1.2 BGD, whereas the maximum capacity is 1.4 BGD, which makes it the largest WRP in the world. The plant is comprised of four secondary treatment batteries, each containing 8 activated sludge tanks and 24 clarifier tanks. In addition, each activated sludge tank has four passes.

Each activated sludge tank is 528 m long, 10.4 m wide and 4.6 m deep, and has a design capacity of 37.5 million gallons per day (MGD) (141,953 m^3/day) and a maximum capacity of 43.8 MGD (165,612 m^3/day). The tanks are operated under fully aerobic conditions without any anoxic or anaerobic zones. The aeration process is achieved by 48 fine-bubble diffusers (aerators) located across the bottom of each tank, and these can be independently adjusted through dedicated valves to manipulate aeration in different zones of the tank. However, the tanks are operated with equal rates of aeration in all zones by default. Also, it is