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Energy efficiency optimisation of wastewater treatment: Study of ATAD

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ABSTRACT

The aim of this paper is to minimise the energy requirement of autothermal thermophilic aerobic digestion (ATAD). To this end, a dynamic ATAD model is presented and assessed. A global sensitivity analysis was performed to identify the operating conditions with the strongest impact on the energy requirements, and thus to choose the most promising optimisation variables. The latter turned out to be the aeration flowrate, the reaction time, and the sludge flowrate. The optimisation problem was formulated following the sequential approach for dynamic optimisation, due to the discontinuous nature of ATAD. The problem was implemented in MATLAB® and solved for two case studies using the *eSS* algorithm, a global scatter search method that alternates with local algorithms (in our case *fmincon*) to refine the best solutions. The two selected full-scale case studies include a single-stage and a two-stage system. For the former, a 22% improvement of the energy requirement was achieved after optimisation, and 18% for the latter. Despite its advantages and common use in other fields, optimisation is still relatively rare in wastewater engineering. In the light of the high, rising cost of wastewater treatment, optimisation should become the norm when it comes to design and operation of wastewater treatment plants.

1. Introduction

1.1. Energy efficiency of wastewater treatment

In the present economic crisis with volatile and rising oil and energy prices, the steady increase of greenhouse gas emissions, and the foreseeable depletion of non-renewable energy sources, it has become evident that more sustainable energy forms and measures are imperative to ensure a sustainable economy for the future. One of those measures is energy efficiency improvement (Commission of the European Communities, 2006). It helps reducing energy requirements often with low investment cost.

The principal concern of the wastewater industry has always been to meet water quality standards in order to keep public trust (Focus on Energy, 2006). Thus, wastewater treatment plants (WWTPs) are usually designed to meet certain effluent requirements, without major energy considerations. As a result, WWTPs are hardly ever designed with energy efficiency in mind. Their design and operation is often based on intuition and experience (Metcalf and Eddy, 2003), rather than on optimal trajectories or set points.

WWTPs are generally very energy-intensive and expensive to operate. As an example, in the US alone WWTPs consume about 2% of the total amount of electricity generated (Batts, Burton, & Jones, 1993). In fact, WWTPs represent the single largest cost to local governments with up to 33% of their total budget (Jones, 1991; M/J Industrial Solutions, 2003; Yonkin, Clubine, & O'Connor, 2008), and their energy consumption is expected to increase by 30–40% in the next 20–30 years (Metcalf and Eddy, 2003).

In the light of these facts, it is surprising that there are very few articles in the available literature devoted to the energy efficiency optimisation of wastewater treatment processes (Descoins, Stephane, Remi, & Marechal, 2010; Fikar, Chachuat, & Latifi, 2005; Holenda, Domokos, Redey, & Fazakas, 2007; Moles, Gutierrez, Alonso, & Banga, 2003, and references cited therein).

Descoins et al. (2010) pointed out that so far the wastewater modelling experts have focused on modelling the effluent wastewater qualities, while the implicit energy aspects have received very little attention.

After labour, electricity is the largest operating cost associated with wastewater treatment with 25–40% of the total (M/J Industrial Solutions, 2003). In the most common type of WWTP, the activated sludge plant, about 50% of this energy is used for aeration purposes (Metcalf and Eddy, 2003).

Among the different treatment stages in a WWTP, sludge treatment generally accounts for a major fraction of the total cost (Barnes, Bliss, Gould, & Vallentine, 1986). There are mainly three methods for sludge treatment: digestion (aerobic or anaerobic, mesophilic or thermophilic), composting, and incineration. In this paper, we will focus on a digestion process known as autothermal thermophilic aerobic digestion (ATAD).

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1.2. The ATAD process

ATAD is an activated sludge process that takes place at thermophilic temperatures. There are several general review articles on its origin, design, and operation (LaPara & Alleman, 1999; Layden, Kelly, Mavinic, Moles, & Barlet, 2007a, 2007b; USEPA, 1990). ATAD technology is applied in both municipal and industrial fields. In the former case, sludge comes from both primary and secondary stages of wastewater treatment. In the latter case, it can be used to treat high-strength slurries, such as pig and cattle slurry.

The objective of the ATAD process is twofold: to stabilise and to pasteurise the sludge. Stabilisation refers to the reduction of the organic matter or volatile solids (VS) concentration below a legally required level, thus eliminating offensive odours and lowering the risk of vector attraction. On the other hand, pasteurisation refers to the reduction of the concentration of certain pathogens below detectable levels via heat treatment. Overall, ATAD displays a better performance in terms of stabilisation and pasteurisation when compared to other sludge treatment processes (Metcalf and Eddy, 2003). ATAD is also more robust and less susceptible to fluctuations of process conditions than other sludge treatment processes (e.g., thermophilic anaerobic digestion).

The principle of the ATAD reaction is basically similar to that of mesophilic digestion: raw sludge containing relatively large amounts of organic matter and pathogens is loaded into a well insulated reactor. The sludge is then mixed and aerated for a certain period of time. The thermophilic microorganisms present in the sludge start then to feed and grow at the expense of oxygen and organic matter. After consuming the substrate, the thermophiles start the so-called endogenous phase: they start consuming their own protoplasm to obtain energy for cell maintenance. It is mainly during this phase that the VS content of the sludge is reduced, hence contributing to sludge stabilisation. Thus, ATAD can be considered as a “feast and famine” process. During their digestion, thermophiles release into the environment vast amounts of metabolic energy rising reactors’ temperatures to the thermophilic range (45–65 °C). These high temperatures are lethal for pathogens, contributing so to sludge pasteurisation.

The end-product of ATAD is considered to be Class A Biosolids: a stable, pasteurised sludge that can be applied on agricultural land without restrictions (USEPA, 1993).

Because of the high oxygen uptake rates (OURs) of thermophilic microorganisms, there is a relatively high energy demand for aeration. As a result, ATAD is an energy-intensive process (Le, 2006; Metcalf and Eddy, 2003).

Conflicting reports in current literature regarding energy efficiency and cost effectiveness of ATAD technology may have contributed to its limited use (Layden et al., 2007b).

2. Motivation and aim

Original research on ATAD systems started as early as the 1960s and 1970s (USEPA, 1990). However, despite this long technological development, ATAD systems have not been optimised (Warakomski, McWhirter, Balan, Swope, & Gyger, 2007). This investigation will focus only on air-driven systems, as most of the available data and publications on ATAD deal with such systems.

There are clear indications that the operating conditions of air-driven ATAD systems have not been exploited:

- *Aeration flowrate*. Conventional systems make use of invariable air supply regardless of the strong variations of bacterial activity in the course of the reaction (Scisson, 2003). This design can result in insufficient oxygen delivery leading to poor stabilisation and odours (Layden et al., 2007a; Scisson, 2003). Another problem can arise with invariable aeration: if the aeration level is designed to satisfy the high OUR period, it will be oversized for the rest of the reaction (Juteau, 2006); this in turn would result in excessive latent heat loss thus lowering reactors’ temperatures (Layden et al., 2007a). More importantly, continuous and invariable aeration is likely to lead to excessive energy consumption (Layden et al., 2007b). On the other hand, a variable aeration level would allow for an optimisation of the hydraulic retention time (HRT) (Kelly & Mavinic, 2003). LaPara and Alleman (1999) concluded that further work is needed to determine the best way to accommodate the enormous OURs of ATAD systems. In other words, more work is necessary to identify the optimal aeration strategy.
- *Sludge flowrate*. The sludge flowrate has been found to influence sludge stabilisation, with higher frequencies leading to higher sludge oxidation rates due to smaller fluctuations of process conditions (Ponti, Sonnleitner, & Fiechter, 1995a). Therefore, continuous operation could display the high degradation potential of ATAD (Ponti, Sonnleitner, & Fiechter, 1995b). Further advantages of continuous operation are avoidance of oxygen-limited conditions, thermal shock reduction, and increased plant capacity (Csikor, Mihaltz, Hanifa, Kovacs, & Dahab, 2002). But most importantly, the sludge flowrate influences the energy requirements of ATAD (Ponti et al., 1995b). In spite of these advantages and because of operating convenience, ATAD systems generally make use of one single volume change per day, thus not allowing a complete exploitation of the thermophiles’ efficiency (Ponti et al., 1995a).
- *Temperature*. Conventional ATAD systems make use of poor temperature regulation sometimes requiring heating and cooling loops (Scisson, 2003). Furthermore, daily loading of the reactors with cold raw sludge results in a thermal shock that significantly decreases reactors’ temperatures. The use of heat integration could lead to smaller thermal shocks and lower operating cost, and it could even be necessary if sludge concentrations are not high enough to sustain thermophilic temperatures (USEPA, 1990). Pre-heating of the influent sludge using the heat from the effluent would reduce the thermal shock in the first stage reactor, and potentially result in shorter hydraulic retention time (HRT) (Layden et al., 2007b); shorter reaction times would lead in turn to lower energy requirements. In spite of this, very few plants make use of heat integration (Layden et al., 2007b).
- *Reaction times*. Shorter reaction times could lead to avoidance of oxygen-limited conditions, reduction of thermal shock, and greater plant capacities (Csikor et al., 2002). Reaction times influence the ultimate product quality in terms of stabilisation and pasteurisation (Ponti et al., 1995a). Nonetheless and due to operating convenience, batch times are set by default to a 24 h cycle. As a result, both stabilisation and pasteurisation levels at the end of the reaction generally exceed legal requirements. These excessively long reaction times result in increased energy requirements.

In the light of these considerations, several researchers agree on the need to identify the optimal operating conditions of ATAD systems (LaPara & Alleman, 1999; Layden et al., 2007a). However, as yet there is no study in the available literature devoted to the optimisation of ATAD (Warakomski et al., 2007).

Given this background, the aim of this paper is to minimise the energy requirement of ATAD systems by altering the operating conditions while complying with treatment objectives, i.e. sludge stabilisation and pasteurisation.