SLUDGE MINIMIZATION BY THERMAL LYSIS DURING BIOLOGICAL WASTEWATER TREATMENT
Experimental Study, Model Set Up and Calibration

Julien Laurent
Institut de Mécanique des Fluides et des Solides, CNRS FRE 3240, 2 rue Boussingault, 67000, Strasbourg, France

Romain Guignard, Magali Casellas, Christophe Dagot
GRESE, Université de Limoges, EA 4330, Site de l'ENSIL, 16 rue Atlantis, 87068 Limoges Cedex, France

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Abstract: Sludge minimization by thermal treatment within activated sludge process was investigated at pilot scale. A 90°C treatment was set up in the return activated sludge loop. When keeping apparent sludge age at 15 days, 90°C treatment decreased sludge production by 30.4%. However, effluent quality was altered. A sludge minimization ASM1 based model was set up and calibrated against experimental data, fractionation experiments allowed us to determine state variables for treated sludge. Biomass lysis explained sludge minimization whereas the decrease of heterotrophs growth rate yielded the higher effluent COD concentration. The calibrated model will then be used to optimize the process.

1 INTRODUCTION

Wastewater treatment with activated sludge processes generates large quantities of excess sludge which must be disposed. Sludge production reached nearly 9 million tons at the end of 2005 in Europe. The disposal of excess sludge constitutes a major issue for wastewater treatment plants operators and communities due to increasing costs, strict regulations, potential environmental hazards and social acceptance problems. Thus, the interest for the development of techniques allowing sludge volume and mass reduction is presently increasing. Thermal treatment is among of the most promising recent technologies for reducing sludge production in wastewater treatment plants (Ødegaard 2004). This process can either be situated on the sludge line in order to reduce sludge mass/volume or in the water line in order to decrease sludge production during biological treatment (Pérez-Elvira et al. 2006). On the sludge line, the main goal is to improve sludge biodegradability prior to anaerobic digestion (Bougrier et al. 2006). On the water line, sludge from aeration tank or secondary settled sludge is treated before recycling in aeration tank (Camacho et al. 2005). In such a process, the main phenomena that could explain sludge production reduction are (Salhi et al. 2003):

- Solubilization of particulate Chemical Oxygen Demand (COD),
- Solubilization plus biodegradation leading to mineralization of organic matter (namely cryptic growth if considering cell lysis),
- Increase of the biodegradability of the inert solid organic fraction,
- Increase of the cell decay rate and/or increase of the maintenance energy requirements leading to a decreased microbial growth for the same substrate consumption.

Low temperature activated sludge thermal treatment yields to several modifications of mixed liquor physico-chemical characteristics: organic compounds solubilization (Paul et al. 2006), cell lysis (Prorot et al. 2008, 2009), modifications of surface properties (Laurent et al. 2009) and anaerobic/aerobic biodegradability improvement (Salsabil et al. 2010).

Dynamic simulation analysis using numerical models is a valuable tool for conception and optimization of control strategies for wastewater treatment plants (WWTPs). However, to date, only

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few attempts to model sludge minimization at source within activated sludge process have been made (Musser & Parker 2009; Camacho et al. 2005). In this study, an Activated Sludge Model n°1 (ASM1) (Henze et al. 2000) based model of sludge minimization by thermal treatment is proposed and validated against experimental data obtained during a pilot study. The model is subsequently used to investigate several scenarios and process configurations for performance optimization.

2 METHODS

2.1 Pilots

Two identical lab-scale activated sludge processes were built and conducted in parallel. One was used as a control and the other included a thermal disintegration step on the sludge recirculation line. The volumes of rectangular aeration tanks and settlers were 13.75 L and 8.3 L respectively. Bubble diffusers located at the bottom of the reactors provided aeration. In the combined system, thermal treatment reactor was continuously included in the recirculation line. Thermal treatment reactor consisted of a stirred 900 mL glass recipient where a heater (1 000 W) was dipped. Temperature was measured by a Pt 100 probe and controlled by means of a on/off temperature regulator.

2.2 Experimental Conditions

The pilots were continuously fed with primary treated wastewater collected each week at the Limoges (France) municipal wastewater treatment plant. This plant has a 285 000 inhabitant-equivalent capacity. Wastewater was kept in a refrigerated (6°C) and agitated tank where it was directly pumped to feed the pilots. Average characteristics of feed wastewater during the experiments were: total COD: 790 ± 140 mg $O_2.L^{-1}$, total suspended solids (TSS): 370 ± 100 $mg.L^{-1}$. Influent flow rate was set up at 21.6 $L.d^{-1}$ corresponding to an influent hydraulic residence time of 15.3 h in the aeration tank. Sludge recirculation from the clarifier was maintained at 100% of feed flow rate, allowing a 60 min return activated sludge retention time in the thermal treatment reactor.

Aeration was operated by repeated aerobic/anoxic cycles (2h/2h) in order to ensure nitrification and denitrification. Air flow rate was adjusted daily in order to have a dissolved oxygen concentration around 2-4 $mg.L^{-1}$ in the reactors during aerated phases (no limitation by oxygen concentration). Solids residence time (i.e. sludge age) was maintained at 15 days throughout the experiments: settled sludge was wasted daily accordingly considering sludge losses through the effluent. The settlers were not considered in sludge age calculations. A preliminary study indicated an equal sludge production in the two processes when thermal treatment was not carried out. The thermal treatment experiment lasted 71 days.

Thermal treatment temperature was fixed at 90°C. The thermal sludge fraction (F) is defined here as the fraction of sludge contained in aeration tank treated each day. It was fixed at 0.2 d^{-1}. The daily duration of heater operation was calculated accordingly. In order to avoid the injection of warm sludge in the aeration tank, return activated sludge was cooled at the outlet of the thermal reactor: the pipe was circulated within fresh water cooled down using a cryostat.

2.3 Calculation Procedure

The daily sludge production was calculated as grams of Volatile Suspended Solids (VSS) produced. It is based on a mass balance taking into account the quantity of wasted sludge, the accumulation within the reactor, and the sludge losses in the treated effluent. As sludge production is directly related to the amount of removed pollution, the sludge production yield was calculated as the ratio of the cumulative sludge production to the cumulative COD removal in the reactors. This last calculation considered a mass balance over COD entering and leaving the system, neglecting the solubilized COD during the treatment: the resulting sludge production was therefore linked to global pollution removal.

2.4 Model Development and Calibration

Experimental data including influent, effluent, activated and return activated sludge were grabbed during whole experiment duration. They were validated through the systematic procedure set up by IWA Task Group on Good Modelling Practice (2011).

2.4.1 Influent Wastewater Characterization

Fractionation of influent wastewater was deduced from experimental measurements (influent and effluent total and dissolved COD as well as TSS, VSS) according to the following calculations:

$$S_i = \text{effluent } COD_d$$
$$S_s = \text{influent } COD_d - S_i$$
$$X_i = (1\text{-}VSS_{inf}/TSS)*COD_t$$
$$X_s = COD_t\text{-}X_i$$
$$X_p = 0$$
$$X_{bh} = 0$$
$$X_{ba} = 0$$
$$S_{nh} = 0.755*NTK$$
$$S_{nd} = 0.396*Norg$$
$$X_{nd} = 0.604*Norg$$
$$S_{no} = 0$$
$$S_{alk} = 30 \text{ mg/L}$$

With NTK = $0.123*COD_t$ and N_{org} = NTK – S_{nh}. (Typical ratios from Hauduc (2011) and Copp (2001)).

2.4.2 Thermal Treatment Model Rationale

Based on the experimental data an ASM1-based model (Henze et al. 2000) of sludge reduction has been developed. It consists of a black box type approach where return activated sludge fractionation as well as some kinetic parameters is modified following 90°C treatment.

The model assumes that a fraction η_{red} of the recycled sludge is thermally treated. A fraction β of heterotrophs (X_h) and nitrifiers (X_a) is destroyed and was determined from results obtained flow cytometry measurements carried out in previous studies (Prorot et al. 2008, 2009). The remaining fraction has an activity level α_{bio}, used to describe the damage that can be caused to cells.

The values of X_p, S_s, S_i, X_{nd}, S_{nd} and S_{nh} of thermal treated activated sludge were assessed by fractionation experiments performed on thermal treated and untreated sludge. All other parameters related to biomass growth and decay were taken as in the original ASM1 model.

2.4.3 Treated Sludge Fractionation Determination

Fractionation experiments were carried out as follows: Activated sludge was sampled in the recirculation line from Limoges WWTP (Total Solids: 6.44 g/L) and treated thermally at 90°C.

The state variables of ASM1 were measured by a method inspired by (Stricker, 2000) and used by (Casellas et al. 2008). Four reactors were filled with sludge according to the data presented in Table 1.

According to (Stricker, 2000) recommendations, the reactors containing filtrated samples were inoculated with activated sludge (1/1000 v/v). The biodegradation tests lasted 30 days. The reactors were continuously aerated and mixed. Soluble and insoluble COD and nitrogen species were monitored every day.

Table 1: Batch reactors configuration for fractionation experiments.

	Reactor 1	*Reactor 2*	*Reactor 3*	*Reactor 4*
Type of sludge	Thermal treated	Thermal treated	Untreated	Untreated
Volume	2L	2L	5L	5L
Filtration	1.2 µm	None	1.2 µm	None
Inoculum	2 mL	None	5 mL	None

2.4.4 Model Implementation

The model was finally incorporated a model comprising a biological tank and a settler. The simulation code was a modification of the script FreeASM1 (original version downloadable at http:// www-imfs.u-strasbg.fr/content/FreeASM1) running under SCILAB software. Settling was modeled by a point settler model which considered a non-settleable sludge fraction. The corresponding parameter f_{ns} was adapted to take into account the presence of small floc fragments observed experimentally.

3 RESULTS

3.1 Pilot Study Results

During pilot study, sludge production was reduced by 30.4% on g VSS produced/g COD removed basis (Figure 1). At the same time, effluent COD (determined after 1.2 µm filtration) drastically increased (Figure 2a).

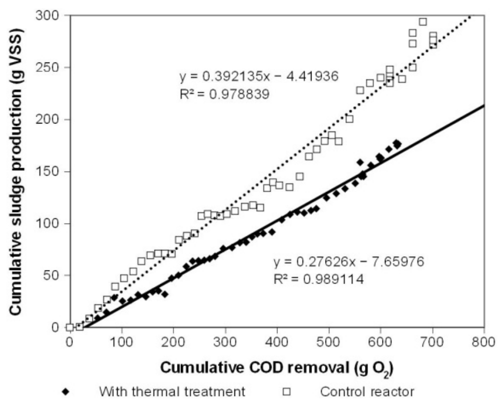

Figure 1: Sludge production yields with and without 90°C treatment of return activated sludge.

Thermal treatment also induced the increase of the non settleable fraction of sludge particulates, leading to higher effluent TSS concentration (Figure 2b).

3.2 Return Activated Sludge Fractionation Following 90°C Treatment

After thermal treatment, return activated sludge is pumped back in the aeration tank and was considered in this study as a substrate for the remaining microorganisms. Therefore, the substrate formed by thermal treated sludge was subjected to fractionation experiments. Thermal treatment is supposed to induce the solubilization of particulate compounds as well as increase the biodegradability of the return activated sludge. The obtained results showed clearly these tendencies.

The solubilization was clearly evidenced by fractionation results. Indeed, 77% of particulate biodegradable substrate (Xp) was converted onto soluble biodegradable substrate (Ss). At the same time, biodegradability of organic compounds was improved as inert fractions dropped after the treatment (-54% for Si, -13% for Xi). Also flow cytometry revealed that about 95% of bacterial cells were lysed following the treatment (Prorot et al. 2008, 2009). These transformations were incorporated in the model.

3.3 Model Calibration

Experimental data validation and model calibration were performed for the two reactors (IWA Task Group on Good Modeling Practice, 2011). Sludge production was initially calibrated by modifying WAS flow rate in order to fit WAS mass load experimental data. The fraction of non settleable solids was calibrated according to the average experimental values of effluent TSS / activated sludge ratio. Nitrogen treatment was not calibrated as it was not systematically monitored during the experiments.

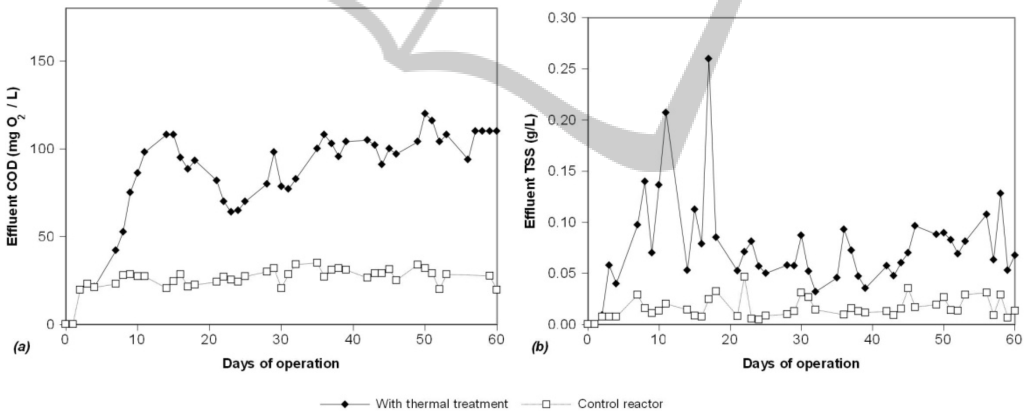

Figure 2: Effluent quality with and without 90°C treatment of return activated sludge: (a) COD (b) TSS.

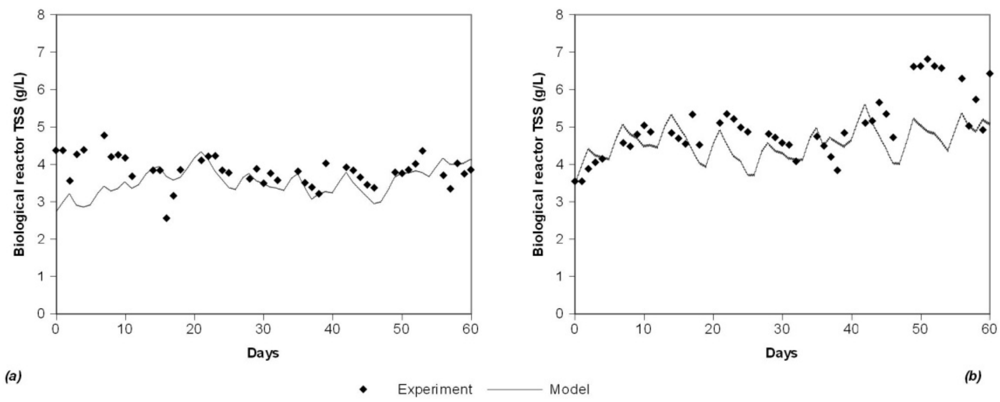

Figure 3: Experimental and modeled activated sludge in the reactors (a) activated sludge + 90°C treatment (b) control pilot.

The model accurately described both sludge production and minimization mechanisms as the relation between modeled and experimental VSS production was about 0.9 in both reactors: Figure 3 shows the accuracy of the modeled TSS concentrations.

A discrepancy between experimental and modeled effluent soluble COD was observed (Figure 4). A reduction factor for both aerobic and anoxic heterotrophs growth kinetics was therefore introduced and yielded a better fitting of experimental data without significant impact on sludge production (5% deviation) (Figure 4). This underlines that the activity of microorganisms was lower in the combined reactor.

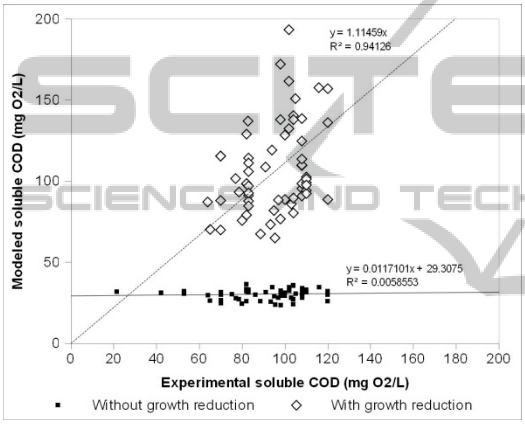

Figure 4: Experimental versus modeled effluent soluble COD for the combined reactor with and without reduction of heterotrophs growth kinetics in the model.

Several hypotheses could explain this phenomenon: bacterial "stress", shift of microbial populations, etc. It is also noteworthy that the thermal treatment model induced a complete loss of nitrification: cell lysis described in the model was sufficient to describe a washout of autotrophic biomass from the reactors, even when the reduction factor of growth kinetic is not introduced. This trend was confirmed by nitrogen species measurements carried out at the end of pilot operation: effluent ammonium concentrations were 35.30 ± 1.77 and 0.40 ± 0.02 mg/L for combined and control reactor respectively.

4 CONCLUSIONS

Sludge thermal treatment (90°C) applied on the water line of an activated sludge process was studied at pilot-scale. Sludge production was effectively lowered by about 30% following thermal treatment in the studied conditions. However, effluent quality was drastically decreased: effluent COD increased as well as TSS concentration due to the generation of non settleable particles. An ASM1 based model of sludge minimization treatment was successfully set up, following a simple systematic procedure, and calibrated over experimental data. This model assumes that sludge reduction is mainly due to the biomass conversion in readily biodegradable substrate followed by its recycling in the biological reactor (solubilisation + cryptic growth). The decrease of COD removal was modeled as a reduction factor for the rates associated to biomass growth. This model will be used in a near future to optimize the process of sludge reduction i.e. obtain a significant sludge minimization while keeping satisfactory effluent quality.

5 NOMENCLATURE

COD_d = dissolved COD (mg O_2/L)
COD_t = total COD (mg O_2/L)
N_{org} = organic nitrogen (mg N/L)
NTK = Kjeldahl nitrogen (mg N/L)
S_i = soluble inert COD (mg O_2/L)
S_{no} = nitrates (mg N/L)
S_{alk} = alkalinity (mg/L)
S_s = soluble biodegradable COD (mg O_2/L)
TSS = volatile suspended solids (mg/L)
VSS = volatile suspended solids (mg/L)
X_i = particulate inert COD (mg O_2/L)
$(1-VSS_{inf}/TSS_{inf})*COD_{t,inf}$
X_s = particulate biodegrabable COD (mg O_2/L)
X_p = bacterial products (mg O_2/L)
X_{bh} = heterotrophs (mg O_2/L)
X_{ba} = autotrophs (mg O_2/L)
S_{nh} = ammonia (mg N/L)
S_{nd} = soluble organic nitrogen (mg N/L)
X_{nd} = particulate organic nitrogen (mg N/L)

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