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# Influence of temperature on the single-stage ATAD process predicted by a thermal equilibrium model

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ABSTRACT

Autothermal thermophilic aerobic digestion (ATAD) is a promising biological process that will produce an effluent satisfying the Class A requirements on pathogen control and land application. The thermophilic temperature in an ATAD reactor is one of the critical factors that can affect the satisfactory operation of the ATAD process. This paper established a thermal equilibrium model to predict the effect of variables on the auto-rising temperature in an ATAD system. The reactors with volumes smaller than 10 $m^3$ could not achieve temperatures higher than 45 °C under ambient temperature of −5 °C. The results showed that for small reactors, the reactor volume played a key role in promoting auto-rising temperature in the winter. Thermophilic temperature achieved in small ATAD reactors did not entirely depend on the heat release from biological activities during degrading organic matters in sludges, but was related to the ambient temperature. The ratios of surface area-to-effective volume less than 2.0 had less impact on the auto-rising temperature of an ATAD reactor. The influence of ambient temperature on the auto-rising reactor temperature decreased with increasing reactor volumes. High oxygen transfer efficiency had a significant influence on the internal temperature rise in an ATAD system, indicating that improving the oxygen transfer efficiency of aeration devices was a key factor to achieve a higher removal rate of volatile solids (VS) during the ATAD process operation. Compared with aeration using cold air, hot air demonstrated a significant effect on maintaining the internal temperature (usually 4–5 °C higher).

## 1. Introduction

Treatment and disposal of sewage sludge produced in municipal wastewater treatment facilities as a by-product of biological process have drawn increasing attention in recent years because of its growing quantity and the more stringent regulations. In order to stabilize sewage sludge, both aerobic and anaerobic digestion processes are commonly used, between which the former is more suitable for small and medium sized municipalities (e.g., 25,000–100,000 population equivalent) owing to its low capital costs, high pathogen reduction rates and simple control requirements (Xu et al., 2013; Liu et al., 2011; Layden et al., 2007a; Kelly and Mavinic, 2003). Among the aerobic processes, the autothermal thermophilic aerobic digestion (ATAD) is a well-recognized process described by USEPA (1990) as a technology that could produce Class A results on pathogen control and land application (Layden et al., 2007a; Kelly et al., 1993; USEPA, 1993, 1990). As a result, ATAD has been widely applied in Europe and North America since the 1990s (Layden et al., 2007a; Kelly and Mavinic, 2003; Skjelhaugen, 1999; Kelly et al., 1993). However, an extensive literature search has found only a few full-scale ATAD systems in operation in China (Cheng et al., 2011; Liu et al., 2011; Cheng and Zhu, 2008). Full-scale and pilot-scale ATAD systems are normally two-stage or multi-stage aerobic thermophilic processes with the volume of each reactor falling between 10 $m^3$ and 600 $m^3$ (Layden et al., 2007b; Kelly and Mavinic, 2003). Some researchers reported information on pilot-scale ATAD processes including a one-stage ATAD digester with an effective volume of 2.25 $m^3$ in 2005 and 10 $m^3$ in 2011 (Cheng et al., 2011; Liu et al., 2011; Cheng and Zhu, 2008). These self-designed ATAD reactors were found to be able to achieve the same level of stabilization as did the two-stage ATAD systems (Liu et al., 2011; Cheng and Zhu, 2008).

Differing from the conventional mesophilic aerobic digestion process, the ATAD process operates in the thermophilic temperature range of 45–65 °C without external heat input because it generates its own heat and is therefore autothermal. It employs

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aeration and significantly reduces the levels of volatile organic fractions and pathogen of the waste to below detectable limits. It utilizes the energy liberated by microorganisms during exothermic biodegradation of organic materials. Therefore, previous research concludes that the thermophilic temperature in an ATAD reactor is a critical factor among all influencing factors and can affect the satisfactory operation of the ATAD process (Juteau, 2006).

The product of reactor temperature and hydraulic retention time is an important indicator parameter for substrate mineralization and sludge stability (Layden et al., 2007b; USEPA, 1990). Thermophilic temperature coupled with short retention time can reduce the effective volume of an ATAD reactor. Similarly, the high temperature with ATAD can contribute to lower liquid viscosity and higher diffusion rates, which enhances biodegradation and promotes better volatile solids decomposition compared to traditional aerobic treatment processes (Layden et al., 2007b). In addition, one of the main expected benefits of ATAD is its efficiency in the killing of pathogenic microorganisms, and it has been recognized in the United States as a process capable of fulfilling Class A biosolids pathogen requirements (USEPA, 1990, 1993). However, extremes in temperature (i.e., >65 °C) are not suitable for achieving solids digestion and can cause the process to become self-limiting and biological activity termination (Layden et al., 2007b; WEF, 1995; USEPA, 1990).

The most important variables affecting the temperature in an ATAD system are related to the concentration of feed sludge due to the quantity of heat released during the exothermic reaction of volatile solid aerobic degradation (Liu et al., 2012a, 2011; Cheng and Zhu, 2008; APHA, AWWA, WEF, 2005; Kelly, 1996). The destruction of volatile solids is the main source of energy, and the quality of the feed material is critical to ensuring that thermophilic temperatures are achieved.

Although previous research on modeling the heat balance is available for describing one-stage and two-stage ATAD processes, or the first ATAD in two sequential stage processes (Gillot and Vanrolleghem, 2003; Messenger et al., 1993, 1990; Vismara, 1985), the impact of the reactor temperature on biological heat generation is still poorly understood with respect to different reactor volumes (including small reactors), given that ATAD is the most cost effective option for small to medium sized reactors. Also, it is not clear about the controlling logic of operating parameters to keep high temperature during the ATAD process operation. In view of the fact that the temperature in an ATAD reactor can be stabilized based on the heat balance of production and loss, in order to maintain high temperature (i.e., 45 °C –65 °C) in ATAD systems for small reactors, it is necessary to establish a thermal equilibrium model on heat balance to understand the influences of variables on the auto-rising temperature ATAD system. Moreover, models can practically guide the design and operation of the ATAD system of a plant. The aim of this study is to develop a mathematical heat balance model to study the effect of parameters of ambient temperature, oxygen transfer efficiency, and reactor structure on the ATAD process performance based on the data from previously reported pilot-scale ATAD reactors (Cheng and Zhu, 2008; Cheng et al., 2011).

## 2. Material and methods

### 2.1. Design of a single-stage ATAD system

The single-stage ATAD was a compact cylinder digester, 2.3 m in diameter and 3.0 m in height with 12.3 $m^3$ in total volume (effective volume: 10 $m^3$), which was fully covered with 60 mm thick insulation material to prevent internal heat from dispersion. Aeration equipment comprising fine bubble disc diffusers was installed at the bottom of the digester to provide continuous aeration at flow rates ranging from 11.6 to 15.6 $m^3\ h^{-1}$ (Cheng and Zhu, 2008). Sludge recirculation devices consisted of a recirculation pump and pipes connecting the bottom to the top of the digester to aid sludge mixing in the digester. Constant stirring was provided from the top of the digester at 60 rpm (Cheng and Zhu, 2008), and an odor controller mounted also on the top of the digester was used to collect effluent gas. The remaining equipment installed included a foam cutter, a temperature indicator, and an oxidation reduction potential (ORP) meter. The schematic of the digester system was shown in Fig. 1 (Liu et al., 2011).

### 2.2. Operation of the single-stage ATAD process

#### 2.2.1. Startup of ATAD digester

Feed sludge consisted of primary sludge and waste biological sludge collected from Qingtan Municipal Sewage Plant equipped with an anaerobic–anoxic–aerobic process in Changzhou, China. The feed sludge was first pre-thickened to 5–8% total solids in a feed tank before being pumped into the single-stage ATAD digester. After loaded with 10 $m^3$ of sludge, the digester was operated in a batch-mode for 30 days accompanied by aeration and sludge recirculation. A gradually rising temperature in the digester was observed, and when the temperature stopped rising, 70% sludge was removed, with the remaining 30% sludge to be used as inoculum.

#### 2.2.2. Operation and mode

After it was replenished with fresh feed sludge to the full capacity (10 $m^3$), the single-stage ATAD digester was experimented with the selected running schemes, which included two kinds of operation modes, i.e., batch and semi-batch. The semi-batch ATAD systems in this study were operated at HRTs of 8, 10 and 15 days, and 0.8, 1.0, and 1.5 $m^3$ of feed sludge, respectively, from the sludge supply tank were pumped into the ATAD digester every 24 h. The batch mode used was to run the single-stage ATAD digester for 30 days. Constant stirring, recirculation of sludge, and continuous aeration were provided during the entire digestion process.

#### 2.2.3. Sludge sample characteristics

The thermal equilibrium model was calibrated using previous results obtained from the running pilot-scale ATAD in China. The physico-chemical characteristics of the sludge were also obtained from the previous results, which indicated 4.6–6.4% total suspended solids (TS), 32.7–45.3 g $L^{-1}$ volatile suspended solids (VS), 60.2–70.2% VS/TS, and pH of 5.9–6.9 (Cheng et al., 2011; Liu et al., 2011; Cheng and Zhu, 2008).

#### 2.2.4. Analysis indexes and method

The concentrations of volatile solid (VS) and total solid (TS) in the feeding and discharged sludge were sampled daily after steady-state operation was established for 15–20 days. The pH of the digestion system was not controlled. The temperature of the ATAD system was monitored twice daily during the entire digestion process. TS and VS were determined according to the Standard Methods (APHA, AWWA, WEF, 2005). Consumption of electrical energy and aeration rates and levels were calculated daily.

## 3. Stoichiometry of biological heat production

### 3.1. Heat balance equation

The heat balance equation can be established based on the energy conservation principle. The heat in a single-stage ATAD digester was generated from the biological exothermic degradation