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Optimum energy integration of thermal hydrolysis through pinch analysis

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ABSTRACT

Anaerobic digestion, a well-established technology to generate biogas from sewage sludge, is constrained by the hydrolysis (or solubilization) stage. Several pretreatments attempt to overcome this limitation, with thermal hydrolysis emerging as the technology of choice due to its techno-economic advantages. The objective of this work is to optimize the integration of this energy intensive pretreatment within the wastewater treatment plant, ensuring that the digestion performance improves in an energy-efficient way. By applying pinch analysis, a methodology to optimize energy systems, a strategy is suggested that selects a second-generation thermal hydrolysis technology designed to recover all process vapors, defines the optimum combined heat and power scheme to ensure an efficient integration and determines the minimum sludge feed concentration to guarantee energy self-sufficiency, the recovery of all waste heat and the minimization of expensive polyelectrolyte use.

1. Introduction

Anaerobic digestion is a well-established technology to generate biogas from organic matter, importantly from sewage sludge. This biogas can be directly used to produce electrical and thermal energy or, after upgrading, it can be transformed into biomethane and be injected in the natural gas grid or used by the automotive sector [1–3].

Anaerobic digestion is limited by the hydrolysis (or solubilization) stage. To overcome this limitation, different types of pretreatments have been suggested: biological (enzymatic), chemical (ozonization, acid or alkaline hydrolysis), physical (ultrasonic, pulses, high-pressure homogenization, centrifuge) and thermal (thermal hydrolysis). An abundance of literature [4–6] discusses the relative merits of each technology. Among those, thermal hydrolysis (TH) has emerged as the pretreatment of choice due to its techno-economic benefits [7]: increased biogas yields, reduced biosolid volume, biosolid pasteurization to EPA Class A standards and at least a twofold increase in organic loading rates to the anaerobic digesters.

Alongside these advantages, the main drawback of thermal hydrolysis is a significant energy consumption [8]. The objective of this work is to optimize the energy integration of the thermal hydrolysis within wastewater treatment plant (WWTP), ensuring that this technology improves the anaerobic digestion performance in an energy-favorable way. To achieve this aim, a two-pronged approach is used: (i) minimize thermal hydrolysis energy consumption by selecting a process design that includes all the energy efficiency measures (ii) optimize the integration of the TH plant within the WWTP energy system, exploiting the synergies with the different combined heat and power (CHP) technologies.

A powerful tool to assist in this endeavor is pinch analysis, an energy systems optimization methodology. Although the application of pinch technology is a standard in process industries, it has been traditionally neglected by the water industry, probably due to the simplicity of its energy systems. Now, the layer of complexity introduced by the integration of thermal hydrolysis pretreatments acts as the prerequisite to fill this gap.

2. Material

The baseline for this work is a WWTP treating the sewage produced by a 1,250,000 population equivalent and operating at the standard design conditions prevalent in Spain. In particular, such WWTP is characterized by the parameters listed in Table 1.

Abbreviations: TH, thermal hydrolysis; WWTP, waste water treatment plant; CHP, combined heat and power; DS, dry solids; VSS, volatile suspended solids.

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Table 1
Main parameters characterizing the base wastewater treatment plant (WWTP) operation.

Sludge	Total flowrate (m^3/d)	1,604
	Primary sludge flowrate (kg DS/d)	35,000
	Primary sludge concentration (% DS)	3
	Secondary sludge flowrate (kg DS/d)	35,000
	Secondary sludge concentration (% DS)	8
Anaerobic digesters	Number of digesters	6
	Volume per digester (m^3)	5,000
	Diameter (m)	27
	Height above ground (m)	7.7
	Height below ground (m)	3.0
	Total digesters volume (m^3)	30,000
	Digestion temperature (ºC)	35
Other parameters	Organic loading rate (kg VSS/$m^3 \cdot$d)	1.6
	Hydraulic residence time (days)	19
	Yield (% VSS)	45
	Productivity (m^3 biogas/m^3 digesters)	0.6
	Specific power consumption (kWh/m^3 wastewater)	0.35

To analyze the impact of different combined heat and power (CHP) technologies, a gas engine and a gas turbine are considered (section 3.2. *Combined heat and power (CHP) technologies*). To properly represent these equipment, and as summarized in Table 2, data has been obtained from two representative manufacturers [9,10] for similarly sized equipment designed to burn biogas.

3. Theory

3.1. Thermal hydrolysis

This pretreatment to the anaerobic digestion improves the sludge biodegradability by means of two distinct mechanisms [11]. The first one is a thermal mechanism, with the sludge maintained at high pressure and temperature during a pre-determined length of time to improve its solubilization. The second one is steam explosion, where a sudden decompression (flash) of the pressurized sludge fractures the cellular structures and makes it easier to digest.

Fig. 1 illustrates the thermal hydrolysis plant fit within the WWTP. Depending on the final objective of the pretreatment, there are two main options [12]: (i) hydrolyze only the secondary sludge when the aim is to increase biogas yields and reduce biosolids volume, as this allows most of the benefit to be captured without the energy consumption associated with treating the primary sludge and (ii) hydrolyze both the primary and the secondary sludge when the additional objective exists to pasteurize the biosolid, yielding an EPA Class A biosolid in return for an increase in steam demand.

The biogas is routinely sent to either a gas engine or a gas turbine to generate power. The associated waste heat can be used to keep the anaerobic digestion temperature and, importantly, to generate steam for the thermal hydrolysis process. The optimum interaction of all these elements is the key to successfully integrate the thermal hydrolysis plant within the WWTP.

3.2. Combined heat and power (CHP) technologies

Wastewater treatment is an energy-intensive endeavor that demands mostly electrical power. An obvious way to reduce the power consumption is to generate it internally from the digesters biogas. This not only reduces the operating costs, but also utilizes a renewable energy source and displaces fossil fuels. While other options such as fuel cells and steam turbines exist, three are the commonly considered CHP technologies to convert anaerobic digester gas to electrical power and process heat. Those are discussed below, and their relative advantages and disadvantages compared (Table 3).

Gas Engines. These reciprocating internal combustion engines are the most widely used and time-tested CHP technology fueled by digester biogas. The vast majority of the applications are of the spark-ignition type, and virtually none of them is of the compression-ignition type (commonly called diesel engines). While in the early days the gas engines where of the rich-burn type (i.e. high fuel-to-air ratio), in the last 30 years manufacturers have developed lean-burn engines, with lower fuel-to-air ratios that result in lower emissions and higher fuel efficiency. Most of the heat, the primary byproduct of the mechanical power generation, is recoverable in two different forms: continuous engine cooling with jacket water and hot exhaust gases.

Gas Turbines. Another well-proven industrial prime mover, its application in WWTPs is far more frequent in the USA than in other regions. Gas turbines consist of three primary sections: a compressor that compresses large quantities of atmospheric air, a combustion chamber where the air ignites the fuel and the expander where mechanical energy is extracted from the combustion gases, driving the compressor and generating power. In contrast to gas engines, which have multiple sources, heat recovery from gas turbines is only available from the exhaust gases. Due to their high temperature, more heat can be recovered in the form of high-pressure steam.

Table 2
Gas engine and gas turbine characteristics.

	Gas engine (Jenbacher J612)	Gas turbine (Solar Centaur 40)
Fuel input (kW)	6,902	12,547
Power output (kW)	3,044	3,500
Thermal output (kW)	2,782	5,625
Power efficiency (%)	44.1%	27.9%
Thermal efficiency (%)	40.3%	44.8%
Cogeneration efficiency (%)	84.4%	72.7%
Exhaust temperature (°C)	425	450