Water Research 118 (2017) 272–288

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Quantitative assessment of energy and resource recovery in wastewater treatment plants based on plant-wide simulations

T. Fernández-Arévalo [a], [b], [*], I. Lizarralde [a], F. Fdz-Polanco [c], S.I. Pérez-Elvira [c], J.M. Garrido [d], S. Puig [e], M. Poch [e], P. Grau [a], E. Ayesa [a]

[a] Ceit-IK4 and Tecnun (University of Navarra), 15 Paseo Manuel de Lardizabal, San Sebastián, 20018, Spain
[b] Conaqua Consulting, Paseo Manuel de Lardizabal 15, San Sebastián, 20018, Spain
[c] Department of Chemical Engineering and Environmental Technology, University of Valladolid, C/Dr. Mergelina, s/n, 47011, Valladolid, Spain
[d] Department of Chemical Engineering, Institute of Technology, University of Santiago de Compostela, 15782, Santiago de Compostela, Spain
[e] LEQUIA, Institute of the Environment, University of Girona, Campus Montilivi, C/Maria Aurèlia Capmany, 69, E-17003, Girona, Catalonia, Spain

ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form
16 March 2017
Accepted 1 April 2017
Available online 6 April 2017

Keywords:
Energy and resource recovery
Global mass and energy balance
Model-based assessment
Plant-wide simulations

ABSTRACT

The growing development of technologies and processes for resource treatment and recovery is offering endless possibilities for creating new plant-wide configurations or modifying existing ones. However, the configurations' complexity, the interrelation between technologies and the influent characteristics turn decision-making into a complex or unobvious process. In this frame, the Plant-Wide Modelling (PWM) library presented in this paper allows a thorough, comprehensive and refined analysis of different plant configurations that are basic aspects in decision-making from an energy and resource recovery perspective. In order to demonstrate the potential of the library and the need to run simulation analyses, this paper carries out a comparative analysis of WWTPs, from a techno-economic point of view. The selected layouts were (1) a conventional WWTP based on a modified version of the Benchmark Simulation Model No. 2, (2) an upgraded or retrofitted WWTP, and (3) a new Wastewater Resource Recovery Facilities (WRRF) concept denominated as C/N/P decoupling WWTP. The study was based on a preliminary analysis of the organic matter and nutrient energy use and recovery options, a comprehensive mass and energy flux distribution analysis in each configuration in order to compare and identify areas for improvement, and a cost analysis of each plant for different influent COD/TN/TP ratios. Analysing the plants from a standpoint of resources and energy utilization, a low utilization of the energy content of the components could be observed in all configurations. In the conventional plant, the COD used to produce biogas was around 29%, the upgraded plant was around 36%, and 34% in the C/N/P decoupling WWTP. With regard to the self-sufficiency of plants, achieving self-sufficiency was not possible in the conventional plant, in the upgraded plant it depended on the influent C/N ratio, and in the C/N/P decoupling WWTP layout self-sufficiency was feasible for almost all influents, especially at high COD concentrations. The plant layouts proposed in this paper are just a sample of the possibilities offered by current technologies. Even so, the library presented here is generic and can be used to construct any other plant layout, provided that a model is available.

1. Introduction

The purpose of the design and upgrade of conventional waste(water) treatment plants (WWTPs) has traditionally been to remove the residual organic compounds and nutrients contained in the water to fulfil quality standards. Resource or energy recovery was focused exclusively on obtaining energy from the biogas produced in anaerobic sludge digestion. This biogas production can supply from a quarter to half of the energy requirements for a

---

[*] Corresponding author. Ceit-IK4 and Tecnun (University of Navarra), 15 Paseo Manuel de Lardizabal, San Sebastián, 20018, Spain.

E-mail addresses: tfernandez@ceit.es (T. Fernández-Arévalo), ilizarralde@ceit.es (I. Lizarralde), ffp@iq.uva.es (F. Fdz-Polanco), sarape@iq.uva.es (S.I. Pérez-Elvira), juanmanuel.garrido@usc.es (J.M. Garrido), sebastia@lequia.udg.cat (S. Puig), manuel.poch@udg.edu (M. Poch), pgrau@ceit.es (P. Grau), eayesa@ceit.es (E. Ayesa).

http://dx.doi.org/10.1016/j.watres.2017.04.001

Nomenclature

$\mathrm{Cost}_{actuator}$	Actuator cost (€ d^{-1})
Cost_{Chem}	Chemical agent specific cost (€ kg^{-1})
Cost_{dosage}	Chemical agent globalcost (€ d^{-1})
Cost_{poly}	Polyelectrolyte specific cost (€ kg^{-1})
d_p	Particle size (m)
D_{pipe}	Pipe diameter (m)
D_{sti}	Impeller diameter (m)
f_{moody}	Friction coefficient
$F_{oversize}$	Oversize factor
G	Gravitational acceleration (m s^{-2})
G	Velocity gradient (s^{-1})
$\overline{H}_{in}$	Input enthalpy (kJ d^{-1})
$\overline{H}_{out}$	Output enthalpy (kJ d^{-1})
HL	Total head loss (m)
HL_f	Friction head loss (m)
HL_l	Minor losses (m)
HL_s	Static head (m)
k_{Chem}	Dosage constant (g_{chem} m^{-3})
$k_{poly,i}$	Polyelectrolite and Total solids concentration ratio for the sludge type i (g_{poly} kg^{-1}_{TSS})
L_{pipe}	Pipe length (m)
$\overline{m}_{i,in}$	Inlet i phase mass flux (gE d^{-1})
MU	Monetary unit (€ d^{-1})
MW_i	Molecular weight of i gaseous phase components
n_{CEPT}	Chemically Enhanced Primary Treatment constant
N_{js}	Impeller rotational speed required to just suspend the particles (Hz, revolutions per sec.)
N_P	Power number
$P_{g,in}$	Absolute gas pressure at the blower/compressor inlet
$P_{g,out}$	Absolute gas pressure at the blower/compressor outlet
Q_w	Water flow rate (m^3 d^{-1})
R	Ideal gas constant (kJ mol^{-1} K^{-1})
S	Impeller/tank geometry factor
Submergence	Submergence (m)
$T_{i,in}$	i phase inflow temperature (K)
$T_{i,out}$	i phase outflow temperature (K)
TSS_i	Total suspended solids concentration in the phase i (gSS m^{-3})
u_w	Average liquid velocity (m s^{-1})
V_i	Volume of the i phase (m^3)
$W_{actuator}$	Electrical consumption of actuators (W_{blow}, W_{pump}, W_{stir}, $W_{turbine}$, etc.) (kJ d^{-1})
W_{blow}	Electrical consumption of blower or compressors (kJ d^{-1})
W_{pump}	Electrical consumption of pump (kJ d^{-1})
W_{stir}	Electrical consumption of stirring (kJ d^{-1})
$W_{turbine}$	Electrical consumption of turbine (kJ d^{-1})
X_{TSS}	Weight percentage of solids in the suspension

Greek Symbols

$\mathrm{gamma}_{g,i}$	Heat capacity ratio of the i gaseous phase components
η_i	Dynamic viscosity (kg m^{-1} s^{-1})
η_{blow}	Efficiency of blowers/compressors
η_{CEPT}	Chemically Enhanced Primary Treatment efficiency
η_{max}	Chemically Enhanced Primary Treatment maximum efficiency
η_{min}	Chemically Enhanced Primary Treatment minimum efficiency
η_{pump}	Efficiency of pumps
η_{stir}	Efficiency of agitation engines
η_{turb}	Efficiency of turbines
υ_i	Kinematic viscosity of the i phase (m^2 s^{-1})
φ_i	Density (g m^{-3})

Subscripts

Comp	Phase components
G	Gaseous phase
M	No. of state variables in the off-gas phase
S	Solid phase
W	Aqueous phase

WWTP with an activated sludge (AS) process (WERF, 2010; McCarty et al., 2011; Puchongkawarin et al., 2015), which needs between 0.3 and 0.6 kWh $m^{-3}_{treated\ water}$ (Foley et al., 2010) to fulfil the energetic needs of the plant. Nevertheless, this value is only one tenth of that associated to the heat of combustion of organic compounds contained in the wastewater (McCarty et al., 2011; Shoener et al., 2014; Kokabian and Gude, 2015). Hence, if a greater proportion of this energy was recovered, treatment plants could become self-sufficient and producers of energy (Logan, 2004; Guest et al., 2009).

Recent concerns about climate change or sustainability have led to an increasing awareness of the importance of resource recovery, energy minimization and environmental impact assessment, which in turn has resulted in tightening effluent standards. Under this changing context, a new paradigm has emerged in which municipal wastewater (MWW), traditionally considered to be a pollution problem and an energy- and chemical-intensive activity with excess sludge disposal issues (Gude, 2015), is starting to be thought of as a continuous and sustainable source of chemical energy and resources (Frijns et al., 2013). As a result, WWTPs are now considered to be Wastewater Resource Recovery Facilities (WRRF) from which valuable products like chemicals, nutrients (mainly phosphorus, P), bioenergy (methane from anaerobic digestion) and bioproducts can be obtained (Keller, 2008; Guest et al., 2009). To make this change possible, the water sector is developing new and innovative treatment technologies, such as energy-efficient nutrient removal or recovery technologies with Anammox, struvite crystallisers, phototropic bacteria, high rate algae systems, sludge pre-treatment processes, or systems for the production of microbial polymers.

The most immediate step for reaching this goal is the updating of existing plants in order to reduce overall operating costs and recover resources. Thanks to the incorporation of new technologies or different plant layouts, energy self-sufficient WWTPs is a feasible goal (Jeppsson et al., 2007). Proof of this comes from the Strass and Wolfgangsee-Ischl WWTPs in Vienna (Wett et al., 2007; Nowak et al., 2011). As stated in the work of Batstone et al. (2015), currently there are two extended philosophies to address the transition from WWTPs to WRRF's. One is the low energy mainline (LEM) configuration, which focuses on using low strength anaerobic digestion processes for treating raw domestic sewage, followed by nutrient removal processes (McCarty et al., 2011). The other is the Partition-Release-Recover (PRR) configuration, which focuses on a first stage of chemical oxygen demand (COD) and nutrient accumulation in the solids, a second stage of release through the digestion process, and a final stage of digestate treatment (Verstraete et al., 2009).

In the literature there are numerous studies comparing different plant layouts and analysing the energy consumption of