Environmental Engineering and Management Journal February 2015, Vol.14, No. 2, 357-360
http://omicron.ch.tuiasi.ro/EEMJ/

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CASE STUDY ON ENERGY EFFICIENCY OF BIOGAS PRODUCTION IN INDUSTRIAL ANAEROBIC DIGESTERS AT MUNICIPAL WASTEWATER TREATMENT PLANTS

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Abstract

Anaerobic digestion was analyzed as the biological process that converts the organic matter present in various types of wastes, activated sludge from the wastewater treatment facilities respectively, into biogas. Latest advancements in the mathematical modeling, simulation and control practices have helped in gaining a better insight of the process. In this paper, an energy efficiency and techno-economical investigation of anaerobic digestion technology for the CHP cogeneration unit, has been done to detect maximum concentrations of methane and to minimize the costs at a Municipal Wastewater Treatment Plant.

Key words: anaerobic digestion, biogas, CHP, energy efficiency, wastewater treatment plant

Received: November, 2014; Revised final: February, 2015; Accepted: February, 2015

1. Introduction

Combined Heat and Power (CHP) involves the simultaneous production of electricity and heat from a single fuel source, such as natural gas, biomass, biogas, coal, or oil. The CHP systems and the technology to treat biogas have improved significantly. CHP systems include different individual components configured into an integrated system as the prime mover, generator, heat recovery setting, and electrical interconnection.

The prime mover that drives the overall system typically identifies the CHP system. With the ability to achieve better results more reliably, cogeneration is a remarkable opportunity for wastewater treatment biogas producers to gain numerous benefits. The main advantages include low-cost electricity production; it also displaces purchased fuels for thermal needs and enhances power reliability for the plant (Bastian et al., 2011).

2. Properties of biogas as fuel for CHP system

Biogas contains 60% to 70% of CH_4, 0.5 % of H_2 and up to 45% of CO_2 (Table 1). After being cleaned of carbon dioxide, this gas becomes a fairly homogeneous fuel containing up to 80% of methane with the calorific capacity of over 25 MJ/m^3. The most important component of biogas, from the calorific point of view is CH_4. The other components are not involved in combustion process, and rather absorb energy from combustion of CH_4 as they leave the process at higher temperature than the one they had before the process (Mihic, 2004).

Thermodynamic properties of CH_4 at 273 K and 1 atm are specific treat c_p = 2.165 kJ/kgK, molar mass M = 16.04 kg/kmol, density ρ = 0.72 kg/m^3,

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individual gas constant R = 0.518 kJ/kgK, lower calorific value H_u = 50000 kJ/kg and $H_{u,n}$ = 36000 kJ/ Nm^3 (Mihic, 2004).

Table 1. Characteristics of anaerobic digester gas (Wiser et al., 2012)

	Digester Gas	
Parameter	***Range***	***Common Value***
Methane, CH_4, percent (dry basis)	60-70	65
Carbon dioxide, CO_2, percent (dry basis)	30-45	39
Nitrogen, N_2, percent (dry basis)	0.2-2.5	0.5
Hydrogen, H_2, percent (dry basis)	0-0.5	0.2
Water vapor, H_2O, percent	5.9-15.3	6
Hydrogen sulfide, H_2S, ppmv (dry basis)	200-3,500	500
Siloxanes, ppbv	200-10,000	800
Specific gravity (based on air = 1.0)	0.8-1.0	0.91

The kinetic model of biogas production is described by the modified Gompertz equation (Eq. 1) (Budiyono et al., 2014; Kwanyong, 2013; Yusuf et al., 2011; Zwietering et al., 1990), where: *P* – cumulative of specific biogas production; *A* – biogas production potential; *U* – maximum biogas production rate; *ë* – the lag phase period or minimum time to produce biogas; *t* – cumulative time for biogas production; e = exp(1).

$$P = A\,exp\left\{-exp\left[\frac{U \times \ddot{e}}{A}(\lambda - t)\right] + 1\right\} \qquad (1)$$

The biogas flowrate can be also calculated by the algebraic equation given in Batstone et al. (2002) (Eq. 2), where: $\rho T_{,8}$, $\rho T_{,9}$ and $\rho T_{,10}$ are the liquid-gas transfer rates and T_{op} = 308.15K.

$$q_{gas} = \frac{RT_{op}}{P_{atm} - p_{gas.H_2O}} V_{liq}\left(\frac{\rho T_{,8}}{16} + \frac{\rho T_{,9}}{64} + \rho T_{,10}\right) \qquad (2)$$

3. Energy efficiency of the CHP biogas system and tehno-economical investigation

3.1. Materials and methods

At an operating temperature, Top= 35°C, an organic load (OL) between 1.6-8.0 kgVSS/m^3, retention time of the sludge RT=15 days, volume of the methanetank V=3,500 m^3, and an average of 1,800 m^3 /day of sludge pumped into the anaerobic digesters, for the period considered, it has been produced a maximum of 9,803 m^3 /day biogas, which represents a biogas flow of aprox. 400 m^3/h. The recirculated biogas, used for mixing purposes inside the digestors is 2,160 m^3 /day, representing 22% of the total biogas produced (Fig. 1). The calculation of total system efficiency is a simple and useful method that evaluates what is produced compared to what is consumed with the following expression (Eq. 3) (Darrow et al., 2014; EPA, 2013), where: W_E – electrical output; Q_{therm}– thermal output; Q_{fuel} –fuel consumption.

$$\eta_0 = \frac{W_E + \sum Q_{therm}}{Q_{fuel}} \qquad (3)$$

The biogas flow leads to an electrical energy output of up to 13,328 kWh/day, through the gas engines 2x330 kW power (P_{el}), that have an electrical energy efficiency conversion between 34-40% (η_{el}). The energy efficiency of the gas engine has a conversion of 38% electrical enegy, (η_{el}), 48% thermal energy (η_{therm}) and 14 % losses, with a total CHP generator efficiency of η_0=96% (EPA, 2014) (Table 2).

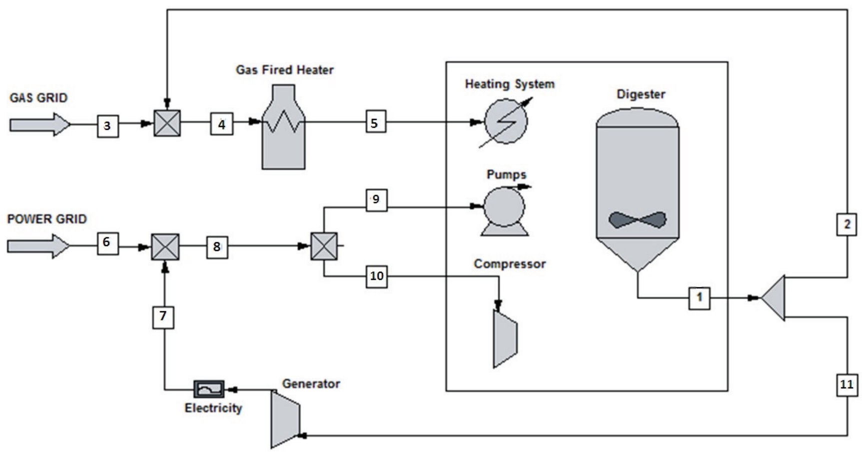

Fig. 1. CHP cogeneration unit scheme: **1**. Biogas generated from digesters; **2**. Amount of biogas directed to the heating system; **3**. Biogas purchased from the national grid; **4**. Biogas utilized for the gas fired heater; **5**. Thermal energy for the heating system; **6**. Electricity purchased from the national grid; **7**. Electricity produced by the generator; **8**. Total amount of electricity; **9**. Electricity utilized for the pumps; **10**. Electricity utilized for the compressor; **11**. Biogas utilized for the generator

Fig. 2. Electrical energy and biogas flowrate in time

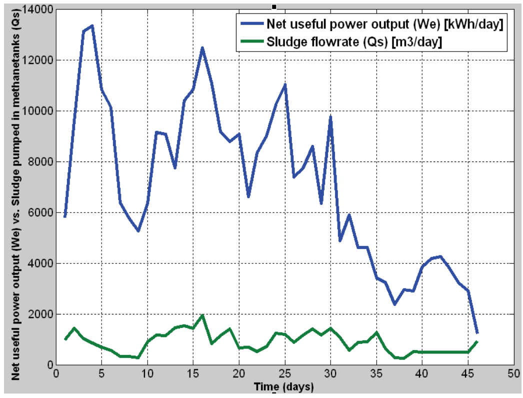

Fig. 3. Electrical energy and sludge flowrate in time

If the total daily average consumption of electricity of the plant reaches 24,570 kWh/day and the electrical energy purchesed from the national grid of 11,457 kWh/day at 0.5194 RON (Transelectrica, 2014), the electrical enegy output from the biogas brings savings of operational costs which could reach up to a maximum of 46.63% or 6,922 RON/day ≈1,573 €/day, for the period of time considered. The energy produced by the CHP biogas system can be used or sold to the national grid and savings can be made through an attractive green certificates market.

The amount of green certificat ranges between 37-55 €/MWh and the number of green certificates ranges between 1-4 in the biomass and biogas market (ANRE, 2014; EU Directive 2009/28/CE; OPCOM, 2014).

Table 2. Energy efficiency of the CHP biogas system

Time (min)	*Electrical Output (kW)*	*Thermal Output (kW)*	*Electrical Efficiency (%)*	*CHP Generator Efficiency (%)*
0	330	369	37.8	96.4
3	330	367	37.8	96.4
15	165	212	34.8	95.6
18	165	208	34.8	95.6
24	248	277	36.8	96.2
27	248	282	36.9	96.2

4. Results and discussion

For an in depth analysis of what specifically influences the biogas production, default electrical energy output and effiency of the CHP system, the following parameters have been found (Kumar, 2012; Mihic, 2004):

a) Technical Parameters

- Concentration of CH_4, composition of biogas; Calorific value of CH_4 (H_u);
- Process parameters: Input parameters, Sludge composition, OL, Sludge flowrate Q_s, and Hydrolysis stage biodegradation fractions;
- Power demand; Demand of low and medium temperature (cogeneration).

b) Economical Parameters

- Price of biogas;
- Price of electrical energy;
- Operational costs.

The rate of decrease in power is largely dependent on the calorific value of the gas. Biogas concentration at 70.10 [%/vol] with a calorific value of H_u = 24.768 kJ/Nm³ ranges as a medium weak gas compared to 76.24 [%/vol] concentration with a calorific value of H_u = 28.723 kJ/Nm³, which causes power reduction.

From the experimental data, for the period considered the maximum net output of electrical power W_e=13.328 kWh/day is obtained at a biogas flow rate of Q_{CH4}=9.803 m^3/hr (Fig. 2) and a default sludge flow rate (Q_s) pumped into the methane tanks of 1947.161 m^3 /day (Fig. 3).

5. Conclusions

The energy (heat+electrical enegy) requirements in a WWTP can be significant. Thus the exploitation of both electrical and thermal energy produced from the CHP system (self-consumption for the heat exchangers) assists to a considerable decrease of biogas plant's operational costs. An electrical energy efficiency of the gas generator η_{el} =38% and η_{therm}=48% have been found.

A total CHP generator efficiency η_0=96% could be observed. The maximum net output of electrical power W_e =13.328 kWh/day is obtained at a biogas flow rate of Q_{CH4}=9.803 m^3 /hr and a default sludge flow rate (Q_s) pumped into the methane tanks of 1947.161 m^3 /day.

Augmentation of biogas can be obtained by maximizing the technical parameters discussed, concentrating the sludge with a higher organic load, and adding municipal biodegradable organic waste to the anaerobic digestion process can be further experimented. Future investigation on the parameters that influence the augmentation of biogas could be researched. The green certificates market makes the CHP biogas technology attractive, and it also becomes an option for the EU Directive 2009/28/CE to utilize energy from renewable sources up to 24% until 2020.

Acknowledgements
This paper is a result of a doctoral research made possible by the financial support of the Sectoral Operational

Program for Human Resources Development 2007-2013, co-financed by the European Social Fund, under the project POSDRU/159/1.5/S/132400- "Young successful researchers – professional development in an international and interdisciplinary environment".

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