BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi,
Tomul LIX (LXIII), Fasc. 1, 2013
Secţia
CONSTRUCŢII DE MAŞINI

BIOWASTES – FROM ENVIRONMENTAL THREAT TO POWER GENERATION

BY

DAN-TEODOR BĂLĂNESCU[1*], PAVEL-DORU VASILIU[2] and CONSTANTIN-EUSEBIU HRIŢCU[2]

[1]"Gheorghe Asachi" Technical University of Iaşi,
Department of Mechanical Engineering and Automotive
[2]INCDT COMOTI - Bucureşti, Iaşi Branch

Received: May 15, 2012
Accepted for publication: June 18, 2012

Abstract. Landfills are important sources of methane, which is a gas with a Global Warming Potential of 23. That is why annihilation of environmental effects of methane must be done. The current methods imply thermal treatment or biological and chemical conversion of biowastes. Beside environmental protection, some methods allow the exploitation of biowastes energetic potential as well. These methods are exposed in the paper. One of the most convenient methods, implying biological and chemical conversion, is anaerobic digestion, which generates biogas. The paper also presents the results of a study regarding replacement of natural gas fuel with biogas in the case of Orenda OGT2500 Gas Turbine.

Key words: wastes, methane, environmental threat, annihilation, biogas, power, home made code, validation.

1. Introduction

The main environmental threat from bio-waste is the production of methane (CH_4), which has the global warming potential (GWP) of 23 in 100

*Corresponding author; *e-mail*: balanescud@yahoo.com

years (Houghton, 2001). This means that each kg of CH_4 warms the earth 23 times as much as the same mass of CO_2 when averaged over 100 years.

The production of CH_4 in landfills accounted for some 3% of total greenhouse gas emissions in the EU-15 in 1995 (Skovgaard, 2008). That is why the European Union issued the Landfill Directive 1999/31/EC, which aims to reduce reliance on landfill as a disposal option. It seeks to decrease the environmental impacts of landfills and reduce the risk to human health while imposing a consistent minimum standard for landfills across the EU. Thus, the Directive obliges Member States to reduce the amount of biodegradable waste they landfill to 35% of 1995 levels by 2016. Beside the reduction of CH_4 emissions, collecting this gas provides a fuel for energy production.

The situation is similar in the case of Municipal / industrial Waste Waters according to the Urban Waste Water Treatment EU Directive of 1991, all agglomerations of more than 2000 peoples had to have a collection and treatment system for the discharged waters. For the 10 new Member States in Central and Eastern Europe, including Romania, staged transition periods were negotiated as part of the EU Accession Treaties, obliging these Member States to comply with the Directive by 2010 to 2015, at the same time providing them considerable financial support by the European Union for planning considerations, design and construction of waste water systems.

In order to implement the EU Directives, the Member States have a number of choices that they can take in terms of alternative treatment for this biodegradable waste, taking into account local conditions such as climatic conditions to the composition of the collected bio-waste. To support the Member States in this legal obligation, the Commission provides criteria, in the form of a guidance document, to help with identifying the environmentally best option for the management of bio-waste in the various countries and regions.

2. Technical Solutions

Our days technical solutions for bio-wastes management involve thermal treatment or biological and chemical conversion. They can be categorized as follows (URS Corp, 2005):

• Thermal treatment

− *Incineration or co-incineration* plant. According to the Waste Incineration Directive 2000/76/EC, incineration plants are dedicated to the thermal treatment of waste and may or may not recover heat generated by combustion. In co-incineration plants (such as cement or lime kilns, steel plants or power plants) the main purpose is energy generation or the production of material products. The Directive sets emission limit values and monitoring requirements for pollutants to air such as dust, NO_x, SO_2, HCl, HF, heavy metals, dioxins and furans. The Directive also sets controls on releases to water resulting from the treatment of the waste gases.

− *Gasification* is a thermal process that converts the majority of carbon from the solid fuel into gaseous form by partial combustion, in a reactor, with air, with oxygen enriched air, with pure oxygen, or by reaction with steam. The process takes place on relatively high temperatures (900…1100°C with air and 1000…1400°C with oxygen).

− *Pyrolysis* is the thermal degradation of the organic material at temperatures of 400…600°C in the complete absence of oxygen, which exclude the possibility of gasification. In the reactor, pyrolysis may occur over a period of time (several minutes or even hours) or very quickly, as in the case of "flash" pyrolysis, where the feedstock encounters an extremely hot internal surface (1000…3000°C) and volatilizes in less than a second. The products of pyrolysis are gas, liquid and solid char with the relative proportions of each depending on the method of pyrolysis and the reaction parameters (temperature, heating rate, pressure and residence time).

− *Plasma technology* implies the heating of a gas (air, oxygen, nitrogen, hydrogen, argon or combinations of these gases) to temperatures above 4000°C by the electrical discharge. The process takes place in a pressurized reactor. The feedstock enters the reactor, where it comes into contact with the hot plasma gas. The amount of air or oxygen used in the torch is controlled to promote gasification reactions. Due to its high heat flux and high temperature, the conversion of carbon-based materials to syngas is almost complete. The inorganic constituents are converted to molten form, then quench-cooled to form a glassy, nonhazardous slag.

− *Thermal Depolymerization* (TDP) is a process of reduction into light crude oil of complex organic materials. The process uses steam under pressure to cook and crack organic chemicals in the absence of oxygen then, by manipulating temperature and pressure, assemble useful selectable hydrocarbon chains. TDP is a closed process which produces liquid fuel and no harmful waste.

• Biological and chemical conversion

− *Composting* is an aerobic microbiological process consisting in the biodegredation of organic matter through a self heating, solid phase. This converts organic matter into a stable humic substance (Martín-Gila, 2008). Composting can be considered as a form of recycling when the stabilised compost is used in agriculture. Beside compost, there are several undesired outputs of the composting process: rejects to landfill from screening, emissions to air - bioaerosols, gaseous emissions (CO_2, CH_4, NH_3 etc.), odours, dust.

− *Anaerobic digestion* (AD) is the bacterial decomposition of organic material in the (relative) absence of oxygen. There are four basic types of microorganisms involved. Hydrolytic bacteria break down complex organic wastes into sugars and amino acids. Fermentative bacteria then convert those products into organic acids. Acidogenic microorganisms convert the acids into hydrogen, carbon dioxide and acetate. Finally, the methanogenic bacteria produce biogas from acetic acid, hydrogen and carbon dioxide. Since these bacteria are sensitive to temperature, this has to be considered in the digestion process. In order to promote bacterial activity, temperatures of at least 20°C are required. Generally, higher temperatures shorten processing time and reduce the required volume of the digester tank by 25% to 40%. Regarding the temperature, bacteria of anaerobic digestion can be divided (Rawlings & Johnson, 2007; Rutz & Janssen, 2008) into psychrophile (25°C), mesophile (32…38°C) and termophile (42…55°C) bacteria. The choice of the process temperature depends on the feedstock and of the utilized digester type. The by-products of AD include biogas as well as a semi-solid residue, referred to as a digestate. With further treatment, the digestate may be used for agricultural / horticultural purposes. The biogas can be used for all the purposes in which natural gas is used because contains about 50…70% CH_4. So, AD is a type of energy recovery and, for this reason, will be further discussed.

3. Biogas

The general anaerobic transformation of the biodegradable organic fraction can be described by the following equation (Kayhanian *et al*., 2007):

$$\begin{aligned} &Organic\ matter + \mathrm{H_2O} + nutrients \rightarrow new\ cells + \\ &\quad + resistant\ organic\ matter + \mathrm{CO_2} + \mathrm{CH_4} + \mathrm{NH_3} + \mathrm{H_2S} + heat \end{aligned} \tag{1}$$

So, the biogas produced contains methane, carbon dioxide and sulphur compounds. A typical composition, by volume, is: CH_4 – 55…70%; CO_2 – 30…45%; H_2S – 200…4000 ppm. The energy content of biogas is 20…25 MJ/m^3_N. Biogas can be used directly for heating and / or power generation or can be upgraded to natural gas quality for injection into the natural gas network as biomethane – Synthetic Natural Gas (SNG) – or for direct use as gaseous biofuel in gas engine powered vehicles (JRC-IET, 2011). The most important upgrade measure is the removal of H_2S, which is a very corrosive component. In the case of the boilers can dissolve the metal parts of the heat exchangers and chimneys because oxidises to form sulphuric acid. In internal combustion engines, H_2S destroys the bearings and other engine parts because reacts with copper alloys.

A number of biogas upgrading technologies operate commercially (*e.g*. absorption and pressure swing adsorption) or are at the demonstration stage (*e.g*. systems using membranes and cryogenics).

The internal energy consumption (electrical and thermal) of an AD plant is about 22% for dry process (dry mass: < 15 %) and 37% for wet process (dry mass: 20…40%). This means that for export are available about 78% of the energy produced for the dry process and 63% for the wet process.

4. Gas Turbine Operating with Biogas

In order to assess the effects of the natural gas replacement with biogas fuel a home made code, named BIOTURBO, was developed. This code calculates the operational parameters of a Gas Turbine Engine. As reference engine the model Orenda OGT2500 (Fig. 1) was chosen. It was considered a desulphurized biogas with the following composition (volume percents): CH_4 = 60%; CO_2 = 32%; H_2 = 6.5%; N_2 = 1.5%.

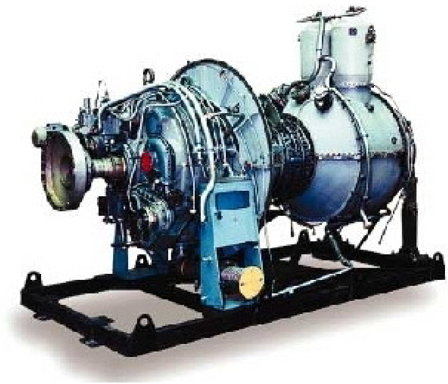

Fig. 1 – Orenda OGT2500 Gas Turbine.

The Low Calorific Value of this fuel is LCV = 20456 kJ/kg while stoichiometric air is L_0 = 7.08 kg of air / kg of fuel.

The calculation algorithms for the processes which take place in the Gas Turbine (compression, combustion and expansion) had been developed proceeding from (Cohen & Rogers, 1996). We consider the expansion process in the Gas Turbine having two stages – one generating the power need for the compressor drive (EEC - energetic equilibrium with the compressor) and the second generating the useful power (UP).

There were assumed the following values:

− ambient pressure and temperature: p_0 = 1.013 bar; t_0 = 15°C
− air mass flow: G_a = 14.9 kg/s
− cooling air mass flow: $G_{ca} = 0.03 \cdot G_a$
− mechanical efficiency of Gas Turbine: η_m = 0.99
− combustion efficiency: ς = 0.94

Besides, the values of turbine inlet temperature and compressor pressure ratio were assumed t_T = 951°C and ε = 12, respectively, as scientific literature indicates (PEI, 2012).

Compressor specific consumption is expressed as

$$W_C = i_C - i_D, \quad [\text{kJ/kg}] \tag{2}$$

while the work per unit air mass flow in EEC stage is calculated with

$$W_{EEC} = \frac{W_C}{\left(1 - G_{ca} / G_a\right) \cdot \left(1 + 1 / \alpha L_0\right) \cdot \eta_m}, \quad \text{[kJ/kg]} \tag{3}$$

Work per unit air mass flow generated in the UP stage is expressed as

$$W_{UP} = i_{UP} - i_E, \quad \text{[kJ/kg]} \tag{4}$$

In Eqs. (2), (3) and (4) are denoted: i_C − compressor outlet enthalpy, [kJ/kg]; i_D − air enthalpy after dynamic compression in the compressor diffuser, [kJ/kg]; i_{UP} − enthalpy of gases at the beginning of the UP stage, [kJ/kg]; i_E − turbine exhaust enthalpy, [kJ/kg]; α − excess air coefficient in the combustor; $\alpha = A/B$, where A and B are expressed as

$$\begin{aligned} A = {} & 22.4 \cdot M_f \cdot \left[\varsigma \cdot LCV + 0.23 \cdot L_0 \cdot S_{\mathrm{O_2}}\right] - \\ & -\left(\sum m \cdot \mathrm{C_m H}_n + \mathrm{CO} + \mathrm{CO_2}\right) \cdot M_{\mathrm{CO_2}} \cdot S_{\mathrm{CO_2}} + \\ & +\left(\sum \frac{n}{2} \cdot \mathrm{C_m H}_n + \mathrm{H_2} + \mathrm{H_2S} + \mathrm{H_2O}\right) \cdot M_{\mathrm{H_2O}} \cdot S_{\mathrm{H_2O}} + \\ & +\left(\mathrm{H_2S} + \mathrm{SO_2}\right) \cdot M_{\mathrm{SO_2}} \cdot S_{\mathrm{SO_2}} + \mathrm{N_2} \cdot M_{\mathrm{N_2}} \cdot S_{\mathrm{N_2}} \end{aligned} \tag{5}$$

$$B = 22.4 \cdot M_f \cdot L_0 \cdot \left[0.23 \cdot S_{\mathrm{O_2}} + 0.77 \cdot S_{\mathrm{N_2}} - \left(i_C - i_0\right)\right] \tag{6}$$

Obviously, the Eqs. (5) and (6) have particular forms imposed by the fuel composition. The following notations were used: M_f − molar mass of the fuel, [kg/kmol]; i_0 − enthalpy of the ambient air, [kJ/kg]; M_i (i = CO_2, H_2O, SO_2, N_2) − molar mass of the gas components, [kg/kmol]; S_i − characteristic sum of component i; is calculated as

$$S_i = \sum_{i=0}^{5} \frac{a_i}{i+1} \cdot \left(T_T^{i+1} - T_0^{i+1}\right), \tag{7}$$

where coefficients a_i are taken from (Ursescu, 1996) and T_T − the turbine inlet temperature, expressed in [K].

The gas mass flow, given by

$$G_g = G_a \cdot \left(1 - G_{ca} / G_a\right) \cdot \left(1 + 1 / \alpha L_0\right), \quad \text{[kg/s]} \tag{8}$$

Power output of the Gas Turbine is calculated with formula

$$P_{GTE} = G_a \cdot W_{UP} \cdot \left(1 - G_{ca} / G_a\right) \cdot \left(1 + 1 / \alpha L_0\right) \cdot \eta_m, \quad \text{[kW]} \tag{9}$$

The fuel consumption and specific fuel consumption are expressed as

$$FC = \frac{3600 \cdot G_a \cdot \left(1 - G_{ca} / G_a\right)}{\alpha L_0}, \quad \text{[kg/h]} \tag{10}$$

respectively

$$SFC = \frac{FC}{P_{GTE}}, \quad \text{[kg/kW h]} \tag{11}$$

The efficiency of the Gas Turbine is given by

$$\eta_{GTE} = \frac{3600 \cdot P_{GTE}}{FC \cdot LCV} \cdot 100, \quad [\%] \tag{12}$$

In order to validate both the calculation algorithm and the code BIOTURBO, the operational parameters of Orenda OGT2500 Gas Turbine were calculated for natural gas fuel. The calculated values were compared with values mentioned in the scientific literature (PEI, 2012). All these data are presented in Table 1.

It can be seen that differences between real data and calculated data are small, in acceptable limits (relative errors ≤ 2.5%). Consequently, we consider that both the calculation algorithm and code BIOTURBO are valid.

The next step of the study was to replace the natural gas fuel with biogas. We proceeded in similar conditions as in the case of natural gas fuel, which means that G_a, T_T and ε have the same values, namely 14.9 kg/s, 951°C and 12, respectively. The results of this new calculus are also presented in Table 1.

Table 1
Characteristic Parameters of Orenda OGT2500 Gas Turbine

Parameter	Values from literature	Values calculated with BIOTURBO code		Relative error columns 2 and 3 [%]
1	2	3	4	5
Fuel	Natural gas	Natural gas	Biogas	–
α	–	3.87	3.75	–
G_g, [kg/s]	14.9	14.82	15.15	0.5
t_E, [°C]	435	446	450	2.5
P_{GTE}, [kW]	2850	2910	3050	2.1
FC, [m^3_N /h]	–	1147.4	1920.7	–
SFC, [m^3_N /kWh]	–	0.395	0.629	–
η_{GTE}, [%]	28.5	28.5	28.9	0

Excepting t_E, which is the turbine exhaust temperature, all parameters from Table 1 are already described.

As can be seen in Table 1, the use of biogas implies only the adjustment/replacement of the fuel supply system, which must ensure a mass flow 2.5 times higher than in the case of natural gas fuel. Obviously, the higher fuel flow requirement is caused by the lower *LCV* of biogas.

The gas mass flow increases with 0.33 kg/s (2.2%) when turbine operates with biogas. This has no significant influence over the flow passing capacity of the turbine.

5. Conclusions

CH_4 released by landfills is a severe threat to environment; each kg of CH_4 warms the earth 23 times as much as 1 kg of CO_2.

There are several methods to annihilate the effect of CH_4, consisting in thermal treatments or biological and chemical conversion. Some methods just eliminate the threat but others exploit the energetic potential of wastes.

One of the most interesting treatments for wastes is anaerobic digestion because generates a clean gas (biogas), which can replace the natural gas in all applications, including reciprocating or gas turbine engines.

In order to estimate the performances of a Gas Turbine engine operating with biogas a calculation algorithm and a home made code (BIOTURBO) were developed and validated.

Operation of Orenda OGT2500 Gas Turbine with biogas instead of natural gas implies only the adjustment/replacement of the fuel supply system. The flow passing capacity of the turbine is not significantly influenced.

REFERENCES

*** JRC-IET, *2011 Technology Map of the European Strategic Energy Technology Plan* (*SET-Plan*). *Technology Descriptions*. Publications Office of the European Union (2011).

*** PEI, *Gas Turbine Technical Data.* Power Engineering International, april 2012, 34−42 (2012).

*** URS Corporation, *Conversion Technology Evaluation Report*. Developed by the Alternative Technology Advisory Subcommittee of the Los Angles County Solid Waste Management Committee/Integrated Waste Management Task Force, http://ladpw.org/epd/tf/Attachments/SubCommittee%20Attachments/CT_Eval_Report.pdf (2005).

Cohen H., Rogers G.F.C., Saravanamuttoo H.I.H., *Gas Turbine Theory*. 4th Edition, Longman Group Limited, 1996.

Houghton J.T., *Climate Change 2001: The Scientific Basis*. Published for the Intergovernmental Panel on Climate Change, Cambridge University Press (2001).

Kayhanian M., Tchobanoglous G., Brown R.C., *Energy Conversion - Biomass Conversion Processes for Energy Recovery*. Taylor & Francis Group, USA, 2007.

Martín-Gila J., Navas-Graciaa L.M., Gómez-Sobrinoa E., Correa-Guimaraesa A., Hernández-Navarroa S., Sánchez-Básconesa M., Ramos-Sánchez M.C., *Composting and Vermicomposting Experiences in the Treatment and Bioconversion of Asphaltens from the Prestige Oil Spill*. Bioresource Technology, **99**, *6*, 1821−1829 (2008).

Rawlings D.E., Johnson B.D., *Biomining.* Springer (2007).

Rutz D., Janssen R., *Biofuel Technology Handbook*. WIP Renewable Energies, Germany (2008).

Skovgaard S., Hedal N., Villanueva A., Andersen F. M., Larsen H., *Municipal Waste Management and Greenhouse Gases*. European Topic Centre on Resource and Waste Management, **1** (2008).

Ursescu D., Homutescu C., Poeată N., *Stabilirea procedeelor de calcul a ciclurilor celor mai uzuale turbine cu gaze în domeniul temperaturii 800 - 2500 K.* Contract de cercetare, beneficiar − I.N.M.T. – Bucureşti (1996).

BIO-DEŞEURILE – DE LA AMENINŢAREA PE CARE O REPREZINTĂ PENTRU MEDIUL ÎNCONJURĂTOR LA PRODUCEREA DE ENERGIE

(Rezumat)

Deşeurile biodegradabile reprezintă o importantă sursă de metan, gaz având un potențial de încălzire globală de 23 mai mare decât cel al bioxidului de carbon. De aceea se impune gestionarea acestor deşeuri în scopul eliminării impactului pe care metanul îl are asupra mediului înconjurător. Metodele actuale de gestionare a deşeurilor biodegradabile presupun tratarea lor termică sau biologică. Unele dintre aceste metode, care sunt prezentate în lucrare, permit, pe lângă protecția mediului, şi exploatarea potențialului energetic al deşeurilor. O astfel de metodă este fermentarea anaerobă care reprezintă un proces biologic de degradare a materiei organice în urma căruia se obține biogazul – un gaz cu conținut mare de metan (55...70%). În urma purificării, biogazul poate fi utilizat drept combustibil, inclusiv pentru motoare cu piston sau turbomotoare cu gaze. Pentru a analiza o aplicație de acest tip, cu turbomotor cu gaze de tip ORENDA OGT2500, s-a conceput un algoritm original de calcul şi s-a realizat aplicația software BIOTURBO, ambele având ca scop estimarea performanțelor unui turbomotor cu gaze funcționând cu orice tip de combustibil gazos, inclusiv biogaz. Validarea algoritmului de calcul şi a aplicației software s-a făcut prin compararea valorilor calculate ale parametrilor de estimare a performanțelor turbomotorului ORENDA OGT2500, funcționând cu gaz natural drept combustibil, cu valorile reale, prezentate în literatura de specialitate. După validare, s-au refăcut calculele, în cazul turbomotorului analizat, considerând un combustibil de tip biogaz, şi s-au tras concluziile.