Economic analysis for a brewery wastewater

ANÁLISE ECONÔMICA DO ESGOTO INDUSTRIAL DE UMA CERVEJARIA

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ABSTRACT

This paper focuses upon mathematical modeling the methane yield from the anaerobic digesting process of a brewery wastewater, whose variables are shown in a parameter diagram format for conveniently separating them in four distinct groups. Basing on mass balance and empirical relations, one builds a numerical simulating system comprising of four differential equations, the anaerobic digesting of organic matter, biogas yielding, methane molar fraction and methane exergy flow. Two dimensionless performance metrics, the organic matter reduction factor, and the methane to biomass yield factor, the former already known and the latter defined in this work, are used to build a phased space plotting for process monitoring purposes. An exergy flow and a specific exergy flow equations are derived based on those dimensionless performance metrics, and then they are plotted together by a numerical simulation. Finally, an economic analysis is performed by using rough estimatives to aid on decision-making processes for harnessing such an energy source for practical usage.

KEYWORDS

Anaerobic digesting. Economic analysis. Industrial wastewater.

RESUMO

Este trabalho visa simular numericamente o fluxo energético potencial oriundo do processo de digestão anaeróbia de uma estação de tratamento de esgoto industrial de uma cervejaria no Brasil, comparando os resultados teóricos a valores experimentais. Baseando-se em balanços de massa e energia, consegue-se simular através de um sistema de equações diferenciais a produção de metano em um processo de digestão anaeróbia. Calcula-se então o fluxo energético potencial daquele esgoto industrial, no qual se baseia uma análise econômica para decidir - se sobre a viabilidade de investimento para aproveitamento energético.

PALAVRAS CHAVE

Digestão anaeróbia. Análise econômica. Esgoto industrial.

INTRODUCTION

The global strategy for sustainable development needs high scale solutions for effectively protecting Earth from human pollution. Anaerobic digesting processes can potentially satisfy the two goals of sustainable development: generating renewable energy and pretreating organic sewage to be disposed of in water bodies.

According to Capra (1996), the anaerobic digesting process is a natural one dating back about 3.8 billions years when the first bacteria evolved in a planet Earth with little oxygen. 1.5 billions years had to pass for increasing the oxygen content in order to enable aerobic digesting.

Actually the anaerobic digesting process is a complex one consisting of several bacterial groups competing with one another for cracking the organic matter down to their nutrients and releasing a gas mixture containing from 50% up to 70% CH_4 and the remaining ones being CO_2 and H_2S.

Nowadays there have been evolving high

performance anaerobic digesting reactors for waste waters which optimize the bacterial work, which are generically called UASB-Upflow Ascendant Sludge Bed, according to Van Haandel and Lettinga (1994). Camargo *et al* (2002) managed to increase an anaerobic digesting rate from 83% to 95% by implementing external stirring through water recirculation. As to the proper temperature for the sludge bed, one can either utilize solar power or methane burning if biogas volume flow is sufficient.

Further optimization of UASB reactors for power generation besides biomass organic reduction involves investigating the utilization of fuel cells coupled to batteries to store electrical power instead of storing biogas in gas chambers, which would double energy efficiency, according to Deo (2004).

Mathematical Models

Singh, Jain and Tauro (1983) proposed a first-order model for substract utilization and biogas formation from cattle waste, which was then modified by Converti, Rezzani and Del Borghi (1998) and Azeiteiro, Capela and Duarte (2001) to comply with non-linearities of the anaerobic digesting. Nevertheless, those papers concentrate on the organic substract utilization and leave little room for the methane yield, which is the focus of this paper.

The equations to be developed are based on high performance anaerobic digesting reactors for waste waters (UASB-type ones) with the following assumptions: a) isothermal processes; b) steady-state biodigester operation; c) disturbance factors as per figure 1 kept controlled at suitable ranges; d) gradients of biomass density and temperature disregarded in the biodigester. For the anaerobic digesting processes being sensitive to temperature and for complying with assumption (a), the time derivatives of all variables are partial ones, so making implicit they do vary with temperature as well.

Figure 1 depicts a parameter diagram for the anaerobic digesting process. Their inputs and outputs to be considered in this work are shown in the left and in the right boxes respectively. The variables in the bottom box are classified as parameters, which means they do not vary beyond process inherent fluctuations. The variables in the upper box are classified as disturbance factors, which means they do interfere with process outputs but positively, so their values ought to be kept at controllable ranges.

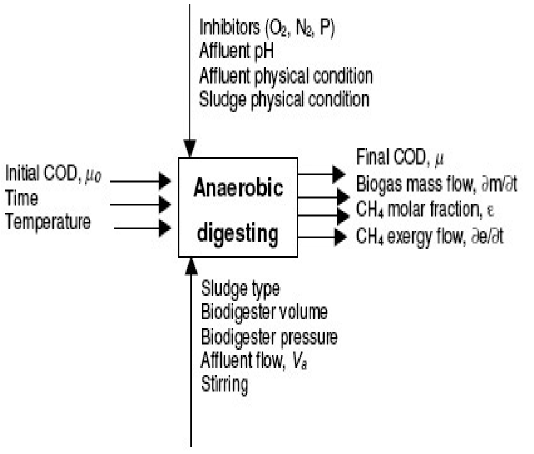

Figure 1 - Parameter diagram for the anaerobic digesting process

Equation 1 models the anaerobic digesting of organic matter, $\mu[ML^{-3}]$, also known as COD – Chemical Oxygen Demand, by an exponential decrease as per Converti, Rezzani and Del Borghi (1998). The a $[M^{1-z}L^{3(z-1)}T^{-1}]$ empirical coefficient depends highly on temperature and the types of organic matter, digesting process. The *z* (AZEITEIRO; CAPELA; DUARTE, 2001) empirical exponent accounts for the best experimental data fitting.

$$\frac{\partial \mu}{\partial t} = -a\mu^{z} \qquad (1)$$

Actually equation 1 is not a model in terms of stemming from an isothermal mass balance over the chemical reactions taking place in the biodigester chamber, which would be quite a complex task for the non-linearities involved. So Converti, Rezzani and Del Borghi (1998) set forth in fitting an exponential decaying differential equation and having added a needed non-linearity represented by a parameter z distinct from unity.

Equation 2 models the biogas mass flow, ?m/?t $[MT^{-1}]$, based on an isothermal mass balance in the biodigester control volume by Deo (2004), where *m* [M] is the biogas mass; *y* (AZEITEIRO; CAPELA; DUARTE, 2001) is an empirical diffusion coefficient of biogas into the effluent; V_a $[L^3T^{-1}]$ is the affluent volume flow; and *p* [T] is the retention time, which is the ratio between the biodigester volume and Va. The á $[T^{-1}]$ empirical coefficient is a digesting time constant.

$$\frac{\partial^2 m}{\partial t^2} = -(1+y)^{-1} V_a \left(\frac{\partial \mu}{\partial t}\right)(1+\beta) \quad (2)$$

Where $= -e^{(t-tp)}$

Equation 2 was checked out against experimental data from a sewage treatment station of a beer plant in Brazil in September 2003. The measured biogas average daily yield was about 3,000m^3 from the following inputs: μ_0=2.88kg/m^3; V =450m^3/h; t =8h. By tweaking the parameters to be y=0.3; a=0.5kg^{-2}m; ?=0.05h^{-1}; z=3; w=1 and taking into account the biogas average specific volume at room temperature and multiplying it to m from integrating equation 2 twice over an eight-hour retention time, one obtains about 990m^3; as the beer plant operates in three shifts, one should multiply that value by three, thus finding a theoretical value of 2,970m^3 a day, which is about 1% different from the measured biogas yield.

Equation 3 models the methane molar fraction in biogas, å (AZEITEIRO; CAPELA; DUARTE, 2001), as per Deo (2004), by setting up a time-dependent relation proportional to *μ*, with *b* [M^{-1}L^{3}T^{-1}], *w* (AZEITEIRO; CAPELA; DUARTE, 2001) being empirical coefficients.

$$\frac{\partial \varepsilon}{\partial t} = b \mu \varepsilon^{w} (1+\beta) \quad (3)$$

Similar to equation 2, equation 3 was checked out against experimental data by making b=0.6m^3/kg.h, resulting about 70% CH_4 molar fraction at eight-hour average retention time, which agrees very closely with the average experimental value.

Equation 4 models the methane exergy flow as per Deo (2004), where h_b is the methane specific lower combustion energy, about 50MJ/kg or 14kWh/kg by Van Wylen and Sonntag (1973).

$$\frac{\partial e}{\partial t} = \varepsilon \frac{\partial m}{\partial t} h_b \quad (4)$$

Considering the same data from the sewage treatment station of the beer plant in Brazil, one finds an average value of 1,550kW depicted from figure 2 over an eight-hour retention time, which means about 37MWh a day. Such an exergy has been burned up in flares thus far.

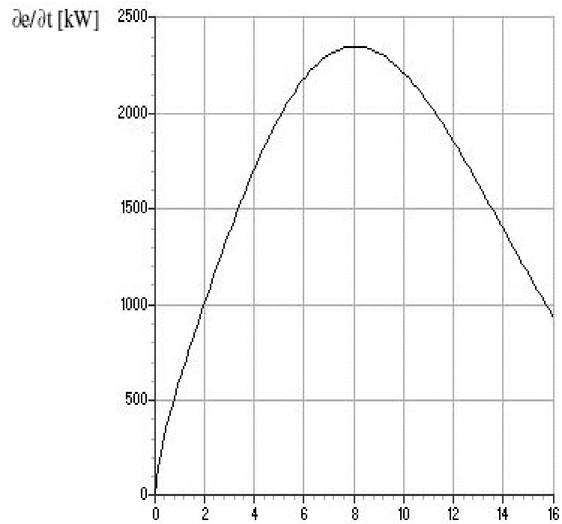

Figure 2 - Power from the anaerobic digestion process of a brewery

Performance metrics

Equation 1 sets the anaerobic digesting of organic matter by modeling the reduction of its organic load or COD, μ, the boundary condition at zero time being μ_0, the initial COD. A performance metric comes up naturally by comparing the two COD extreme values, the initial one and the final one after a determined retention time, as to equation 5. Thus the smaller the final COD the better.

$$\eta_\mu = 1 - \frac{\mu}{\mu_0}$$

By multiplying ?m/?t from equation 2 and μ from equation 3, one obtains the methane mass flow, which can be divided by the product between V_a and μ_0, which means the affluent mass flow, in order to develop another performance metric relating both mass flows as to equation 6. Thus the larger such a value the more methane is yielded from a determined affluent mass flow.

$$\eta_\varepsilon = \varepsilon \frac{\partial m / \partial t}{V_a \mu_0}$$

Figure 3 exemplifies a phased space plotting of the above performance metrics. The upper limit for $ç_å$, 0.25, refers to the stechiometric one according to Van Haandel and Lettinga (1994). The upper limit for $ç_\mu$, 1.00, the current processes being about 0.85 average without external stirring.

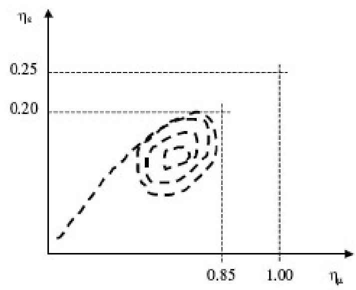

Figure 3 - Performance metrics in a phased space plotting

Such a plotting can be used as a process monitoring visual chart: after process startup phase represented by the ascending portion of the curve, it should go on a pattern which shows the expected process fluctuations, otherwise the process shall not have reached a stable configuration.

By combining equations 4 and 6, one obtains another equation for the exergy flow as to equation 7. By dividing equation 7 by the affluent mass flow given by the product between V_a and μ_0, one obtains equation 8, which means a specific exergy, or how much of the affluent mass flow turns out to be converted into exergy per mass unit. equation 8 is useful for estimating a specific exergy output for an anaerobic digesting process. With $ç_{â}$ being 15%, such a specific exergy output would be about 2kWh/kg biomass.

Numerical simulation

By utilizing a specific software for solving differential equations, one can plot the outputs from each equations 1 to 4 thus far developed and their combinations easily. Nevertheless, equations 5 and 6 comprise all the variables in dimensionless outputs, which is very convenient to analyze. Figure 4 shows the plotting of equations 5 and 6 with the following parameters: μ_0=1.5kg/m^3; V_a=1.5m^3/h; t_p=20h; y=0.3; a=0.5kg^{-2}m^{6}h-1; b=0.6m^3/kg.h; ?= 0.05h^{-1}; z=3; w=1.

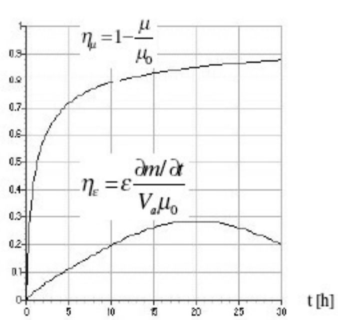

Figure 4 - Performance metric for the anaerobic digestion

Economic Analysis

In order to harness the 1.55MW biogas power from the anaerobic digesting of the wastewater from that brewery in Brazil, one needs first to forecast investment and operational cash flows. Then an economic performance metric should be applied and compared to the investors' expectations. It must be emphasized that the cash flow data given here are indicative and they can be used for first estimates only. Therefore, the final decision ought to be based on values provided by companies which will supply, install and perhaps maintain the equipments.

Based on the EDUCOGEN (VAN WYLEN; SONNTAG, 1973) compilation work, a 1.55MW power relates to a •$1500/kW specific investment for steam turbine systems, thus giving an investment amount of $2.3M, with ±25% uncertainty zone. Such a project investment can be negociated by the carbon credit process by which another company invests on enviromental friendly projects of another one in exchange for its polluting processes to carry on.

As to the operational cash flows, there are the maintenance costs as well as the costdown ones from using the biogas power instead of the one from the electrical grid. For steam turbine systems, there is a •$2/MWh specific maintenance cost as per EDUCOGEN (VAN WYLEN; SONNTAG, 1973), and a grid electricity tariff of •$380/MWh as per EDUCOGEN (VAN WYLEN; SONNTAG, 1973), thus resulting on a specific net cash flow of •$378/MWh, to which one may also apply a ±25% uncertainty zone. The 1.55MW power from the anaerobic digester feeds a steam turbine system, which in turn yields about 0.465MW electrical power. Assuming 8,000 operational hours a year gives 3,720MWh/year, which means an initial net cash flow of about •$1.4M/year. As time goes by, let that net cash flow decrease at a 5% rate/year due to either increasing maintenance costs or decreasing of the grid electricity tariff. All the net cash flow data are summarized in table 1, along with their expected and variance values. The last line shows the Internal Rate

ROI vs. time curves whose roots are also the payback values.

One should compare the economic performance metrics, discounted payback or ROI, to the investors' ones. If either the investors' payback specification is below three years or a larger than 50% ROI after five years, then the project shall go ahead. Also note the IRR values are higher than the assumed capital cost from the third year onward.

Return-IRR values, which should be higher than the capital cost within a defined time frame for the project to be approved.

As to the capital cost, let it be 20% a year initially and decreasing at a 1% rate/year in order to account for a project risk lowering due to better forecasting quality along time. Figure 5 depicts the Net Present Value-NPV vs. time curves whose roots are the payback values. Figure 6 depicts the Return Over Investment-

Figure 5 – Payback range within 95% confidence interval under NPV metric

Figure 6 – Payback range within 95% confidence interval under ROI metric

	0	1	2	3	4	5	6	7	8	9	10
FC_0	-2.30	1.40	1.33	1.26	1.20	1.14	1.08	1.03	0.98	0.93	0.88
FC_-	-2.88	1.05	1.00	0.95	0.90	0.86	0.81	0.77	0.73	0.70	0.66
FC_+	-1.73	1.75	1.66	1.58	1.50	1.43	1.35	1.29	1.22	1.16	1.10
E(FC)	-2.30	1.40	1.33	1.26	1.20	1.14	1.08	1.03	0.98	0.93	0.88
$S^2(FC)$	0.11	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02
E(IRR)	-	-39.1%	12.3%	34.3%	44.5%	49.6%	52.3%	53.8%	54.6%	55.1%	55.4%

Table 1 - Net cash flow values and statistical figures

Notes:

FC_0: most probable cash flow value, with 2/3 likehood to happen;
FC_-: lower cash flow value, with 1/6 likehood to happen;
FC_+: upper cash flow value, with 1/6 likehood to happen;
E(FC): expected cash flow value;
S^2(FC): cash flow sample variance;
E(IRR): expected Internal Return Rate-IRR value.

Conclusions

The methane yield from an anaerobic digesting process in a brewery in Brazil was calculated by solving a four-differential equation set comprised of the COD reduction, biogas yield, methane molar fraction and methane exergy flow. The theoretical value for the methane yield differed about 1% from the measured one. These four equations brought about dimensionless performance metrics for the COD reduction and methane yield, which were then plotted together. A specific methane exergy relation was derived for quick evaluating the energy potential of a given biomass yield, thus allowing decision-making processes for biomass energy investments to be made.

An economic analysis was performed by using rough estimatives in a first evaluation for harnessing the exergy contained in the wastewater from a brewery, the conclusion being the investment amount would be paid back in less than three years.

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Análise econômica. Digestão anaeróbia. Esgoto industrial.

References

AZEITEIRO, C.; CAPELA, I. F.; DUARTE, A. C. Dynamic model simulations as a tool for evaluating the stability of an anaerobic process. *Water SA*, v. 27, n. 1, p. 109-114, 2001.

CAMARGO, E. F. M; RATUSZNEI, S. M.; RODRIGUES, J. D. A.; ZAIAT, M.; BORZANI, W. Treatment of low strength wasterwater using imobilized biomass in a sequencing batch external loop reactor: influence of the medium superficial velocity on the stability and performance. *Brazilian Journal of Chemical Engineering*, v. 19, n. 3, p. 267-275, jul./set. 2002.

CAPRA, F. *A teia da vida. Uma nova compreensão científica dos sistemas vivos.* São Paulo: Pensamento-Cultrix, 1996.

CONVERTI, A.; REZZANI, L. G.; DEL BORGHI, M. Kinetic study on methane fermentation of pre-hydrolyzed lignocellulosics. *Journal of Air & Waste Management Association*, v. 48, p. 366-370, 1998.

DEO, V. F. *Análise numérica e econômica da produção de metano por biodigestão anaeróbia.* 2004. Dissertação (Mestrado em Engenharia Mecânica, sub-área Energia) – Departamento de Engenharia Mecânica, Universidade de Taubaté, Taubaté, 2004.

SINGH, R.; JAIN, M. K.; TAURO, P. Mathematical modelling of substrate utilization and biogas formation from cattle waste. *Water Res.*, v. 17, p. 349-351, 1983.

VAN HAANDEL, A. C.; LETTINGA, G. *Tratamento anaeróbio de esgoto:* um manual para regiões de clima quente. v. 1. Campina Grande: Universidade Federal da Paraíba, 1994.

VAN WYLEN, G. J. ; SONNTAG, R. E. *Fundamentals of classical thermodynamics.* New York: John Wiley & Sons, 1973.