WASTEWATER CHEMICALLY ENHANCED PRIMARY TREATMENT RENEWABILITY ASSESSMENT BY EXERGOENVIRONMENTAL ANALYSIS

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Abstract. *This paper presents a scientific methodology, with well defined criteria, to assess and quantify the environmental performance and renewability of chemically enhanced primary treatment (CEPT) on a single base: the exergy. The CEPT is the improvement of primary sedimentation process, by the application of chemical coagulants. In this work, the environmental performance was measured by calculating the environmental exergy efficiency defined as the exergy ratio of the useful effect of the process to the total exergy consumed by human and natural resources, including all the exergy inputs. The renewability calculation was done using the renewability exergy index defined as the exergy ratio of the products to the sum of the non-renewable exergy, destroyed exergy, deactivation exergy and the emissions and waste exergy. The methodology was applied to physicochemical (CEPT) process located in the urban area of Cali (Colombia). The results analysis showed that the proposed methodology is a useful tool in the evaluation of environmental performance and renewability of wastewater treatment processes.*

Keywords*: environmental exergy efficiency, renewability exergy index, chemically enhanced primary treatment, wastewater treatment systems.*

1. INTRODUCTION

The high cost and complexity of conventional wastewater treatment have hampered developing countries wastewater treatment. This limitation is being resolved through the use of physico-chemical process "Chemically Enhanced Primary Treatment" (CEPT) as an alternative to conventional secondary and tertiary treatments Tsukamoto (2002).

Improvement in global health, sanitation and consequent reduction in the spread of disease depends largely on good hygiene practices, availability of health facilities, and reliable collection and treatment of wastewater. The World Health Organization (WHO) estimates that 2.4 billion people lack access to any type of sanitation equipment Muga and Mihelcic (2008)

There is an increasing demand for more sustainable wastewater treatment systems. However, the criteria needed to characterize such a system are not fully developed. is a challenge designing wastewater treatment systems sustainable that address the positive effects to the environment, society and economy. The visions more futuristic of the wastewater treatment systems value the level of ability the operation staff of the plant, the jobs in the community, aesthetics of the physical structure of the plant, the minimization the atmospherics emissions, operations costs and the energy use, thus, the treatment system maximization. Several authors have proposed different wastewater treatment systems sustainability indexes, which includes the exergy concept (Lundin *et al.,* 1997; Balkema *et al.,* 2002; Palme *et al.,* 2005; Muga and Mihelcic, 2008). Hellström (1997) showed how an exergy analysis could be used to estimate the consumption of physical resources in a wastewater treatment plant.

The concept of exergy has been used in environmental and ecological fields (Jorgensen, 1988; Jorgensen, 1992a,b), as an ecological indicator and goal function in the ecological modeling for aquatic systems (Bendoricchio and Jorgensen, 1997; Jorgensen and Nielsen, 2007). In addition, it has been used for water quality evaluation, illustrating the relation between exergy and the water quality parameters as COD (Chemical Oxygen Demand), BOD (Biochemical Oxygen Demand), TOC (Total Organic Carbon) (Tai *et al.,* 1986; Chen and JI, 2007; Huang *et al.,* 2007; Chen *et al,* 2007**;** Zaleta-Aguilar *et al,* 1998**;** Gallegos-Muñoz *et al,* 2003**;** Valero *et al,* 2006**;** Hellström, 2003). Others authors have presented renewability exergy indexes for processes different (Dewulf and Van Langenhove, 2005; Manish *et al.*, 2006; Chen *et al.*, 2009; Torio *et al.*, 2009). According to Szargut *et al.,* 1988, exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with those components of nature.

In this work, the environmental exergy efficiency and the renewability exergy index are used to evaluate the environmental performance and the renewability of the Wastewater Treatment Plant Cañaveralejo, located in the Urban area of Cali (Colombia).

2. WASTEWATER TREATMENT PROCESSES

The analysed Wastewater Treatment Process (WTP) is the WTP Cañaveralejo (Fig. 1) (Cali, Colombia).

Figure 1 illustrate the process of the WTP Cañaveralejo, that is a chemically enhanced primary treatment (CEPT), The Preliminary Treatment consists of two phases: screening and sand removal. Screening removes large solids, which are retained by the screens. The main reasons for the screening are to protect the pumps and tubes, later treatment units and the tanks. The sand is removed by sedimentation. The aims of sand removal are to protect the equipment from wear and turbulence, eliminate or reduce the risk of blockages in pipes, tanks, siphons and passages, and simplify the liquid transportation, especially transfer of sludge. The Primary Treatment consists of primary settling tank. Sewage flows slowly through the tanks, allowing suspended solids to gradually settle to the bottom of the tank. This solid mass, called primary sludge, can be consolidated at the bottom of the tank and sent directly for digestion, or can be sent to the consolidation tanks. A large part of these solids is made up of organic matter. The retained solids are continuously removed in buckets. In physico-chemical treatment, is removed the solid matter by means of processes of coagulation, flocculation and sedimentation. Coagulation are employed in low concentrations iron salts, alone or in combination with cationic polymers, the flocculation is achieved after adding anionic polymers and the action of electrostatic forces that promote the formation of flakes of coagulated particles larger, and the sedimentation there is increasing the speed of sedimentation of particles due to the increase of its size. The unit of settlement is similar to the conventional unit of decanting, adding only the system of dosage and application of coagulants and polymers (Cete Poli/UFRJ, 2001).

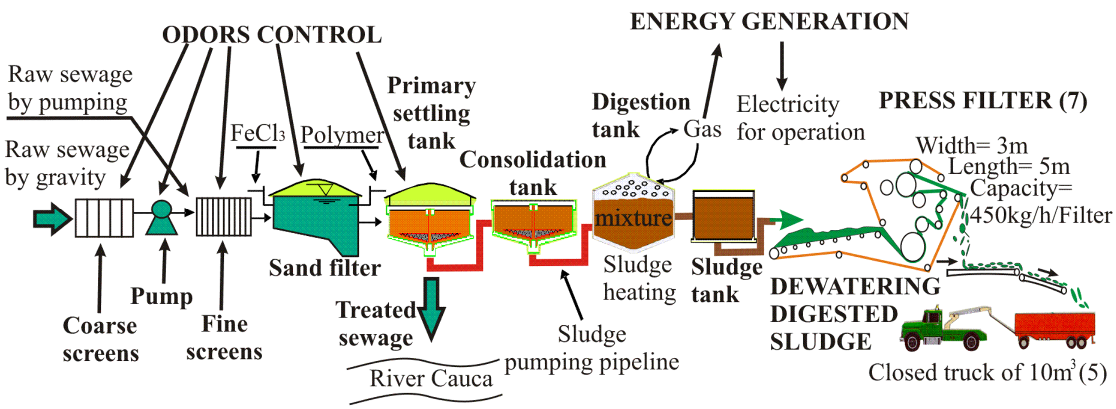

Figure 1. Cañaveralejo Wastewater Treatment Plant (EMCALI, 2001)

Tables 1, 2, present the raw and treated sewage composition as well as the sludge composition of Cañaveralejo WTP.

Table 1. Composition of the raw and treated sewage for Cañaveralejo WTP.

	Composition (mol L^{-1})	
	Raw sewage	Treated sewage
COD	2.20E-03	1.39E-03
$CaCO_3$	1.93E-03	1.86E-03
Cl	1.51E-03	1.52E-03
Cd	5.67E-08	5.34E-08
Ni	7.86E-07	6.01E-07
Ag	1.11E-07	1.11E-07
Zn	2.56E-06	1.24E-06
Pb	5.31E-07	5.31E-07
Cu	4.64E-07	2.36E-07
Cr	1.16E-06	9.14E-07
Fe	4.95E-05	4.85E-05
P	1.76E-04	1.29E-04
Detergent	1.62E-04	1.25E-04
Hg	8.47E-10	8.47E-10

Table 2. Sludge composition of Cañaveralejo WTP

Components	Composition (mol kg^{-1})
COD (mol L^{-1})	1.73E-01
Cd	9.79E-05
Pb	1.69E-03
Cu	4.07E-03
Cr	2.16E-03
Fe	8.20E-01
Ni	1.69E-03
Zn	1.38E-02
Ag	2.23E-04
Hg	2.38E-07

3. EXERGOENVIRONMENTAL ANALYSIS OF WASTEWATER TREATMENT PROCESSES

3.1 Exergy based index

The environmental performance and renewability of the wastewater treatment process is done by means of evaluating the environmental exergy efficiency ($\eta_{env,exerg}$) as proposed by (Makarytchev, 1997; Mora and Oliveira, 2004) and of the renewability exergy index (λ) as proposed by (Velásquez et al., 2007, 2008). The environmental exergy efficiency is defined as the ratio of the final product exergy (or useful effect of a process) to the total exergy of natural and human resources consumed, including all the exergy inputs. That ratio is also an indication of the theoretical potential of future improvements for a process. The environmental exergy efficiency is calculated according to Eq. (1).

$$\eta_{env,exerg} = B_{product} / (B_{Nat,Res} + B_{Prep} + B_{Deact} + B_{Disp}) \quad (1)$$

Where: $B_{Deact.}$= exergy rate/flowrate of additional natural resources destroyed during waste deactivation [kW]; B_{Disp} = exergy rate/flowrate related to waste disposal of the process [kW]; $B_{Nat.Res}$ = exergy rate/flowrate of the natural resources consumed by the processes [kW]; B_{Prep} = exergy rate/flowrate required for extraction and preparation of the natural resources [kW]; $B_{Product}$ = exergy rate/flowrate of the useful effect of a process [kW].

The renewability calculation was done using the renewability exergy index defined as the exergy ratio of the products to the sum of the non-renewable exergy, destroyed exergy, deactivation exergy and the emissions and waste exergy. The renewability exergy index is calculated according to Eq. (2).

$$\lambda = B_{product} / (B_{Non\text{-}Renew} + B_{Destr} + B_{Deact} + B_{Emiss/Wast}) \quad (2)$$

Where: $B_{Deact.}$= exergy rate/flowrate of additional natural resources destroyed during emissions and waste deactivation [kW]; B_{Destr} = destroyed exergy rate in the wastewater treatment process [kW]; $B_{Non\text{-}Renew}$ = exergy rate/flowrate of the non-renewable resources consumed by the wastewater treatment process [kW]; $B_{Emiss/Wast}$ = exergy of the emissions and wastes that are not treated [kW].

The renewability exergy index value may be in the following ranges:

$0 < \lambda < 1$ when $(B_{Non\text{-}Renew} + B_{Destr} + B_{Deact} + B_{Emiss/Wast}) > B_{product}$. This is the case of sewage treatment system environmentally unfavorable.

$\lambda > 1$ when $B_{product} > (B_{Non\text{-}Renew} + B_{Destr} + B_{Deact} + B_{Emiss/Wast})$; This scenario happens when the sewage treatment system is environmentally favorable.

When all the processes of the sewage treatment system are internally and externally reversible, using only non-renewable inputs: $\lambda = 1$. In the case where all the process of the sewage treatment system are internally and externally reversible and all exergy inputs are due to renewable sources, then $\lambda \rightarrow \infty$ (Pellegrini, 2009).

3.2 Exergy evaluation of the environmental performance and renewability of the WTP

The analysis of the environmental performance and renewability was carried out for the WTP Cañaveralejo. Based on the data supplied by EMCALI (Empresas Municipales de Cali, Colombia), an exergy analysis was realized considering operation in steady state conditions and using annual average data of process. The chemical exergy of organic matter in the wastewater ($B_{org,mat}$ = chemical exergy flowrate of organic matter [kW]) was calculated according to the relation between chemical exergy of organic substance and the COD utilizing Eq. (3), as proposed by Tai *et al.,* 1986:

$$B_{org,mat.} = 13.6COD \quad (3)$$

The molecular mass of sewage was assumed as of the substance $C_{10}H_{18}O_3N$, the exergy of inorganic substances for the raw and treated sewage was calculated considering real mixture (activity ≠ molar fraction) and 298.15 K as reference temperature. The exergy of sludge was calculated considering ideal mixture (activity = molar fraction), and The exergy flows due biogas and chemicals were calculated according to standard chemical exergy data presented by Szargut *et al.,* 1988. With the information generated by this exergy analysis, the environmental exergy efficiency and renewability exergy index were determined.

In Table 3, 4 and 5 are presented the calculation of the raw sewage, treated sewage and dewatering sludge exergy flows of Cañaveralejo Wastewater Treatment Process.

Table 3. Exergy of the raw sewage

Components	x_i (molmol^{-1})	Specific chemical exergy (kJmol^{-1})	Total molar chemical exergy (kJmol^{-1})	Specific chemical exergy (kJL^{-1})
COD	3.65E-01	2720.0	9.88E+02	2.18E+00
$CaCO_3$	3.19E-01	1.0	-4.93E+00	0
Cl	2.50E-01	87.1	17.8E+00	2.69E-02
Cd	9.40E-06	293.5	2.37E-03	1.34E-10
Ni	1.30E-04	232.7	2.58E-02	2.02E-08
Ag	1.84E-05	70.2	5.62E-04	6.26E-11
Zn	4.24E-04	339.2	1.30E-01	3.00E-07
Pb	8.80E-05	232.8	1.73E-02	9.20E-09
Cu	7.69E-05	134.2	7.54E-03	3.50E-09
Cr	1.92E-04	544.3	9.78E-02	1.00E-07
Fe	8.21E-03	376.4	2.89E+00	1.43E-04
Alcohol	6.62E-05	3128.5	2.05E-01	8.18E-08
P	2.92E-02	869.7	24.8E+00	4.37E-03
Detergent	2.68E-02	74.9	1.43E+00	2.32E-04
Hg	1.00E-07	115.9	9.00E-06	7.63E-15
Overall	1.00E+00		1.03E+03	2.20E+00

Table 4. Exergy of the treated sewage

Components	x_i (molmol^{-1})	Specific chemical exergy (kJmol^{-1})	Total molar chemical exergy (kJmol^{-1})	Specific chemical exergy (kJL^{-1})
COD	2.73E-01	2716.1	7.38E+02	1.02E+00
$CaCO_3$	3.66E-01	1.0	-5.64E+00	0
Cl	3.00E-01	87.1	21.3E+00	3.25E-02
Cd	1.05E-05	293.5	2.65E-03	1.41E-10
Ni	1.19E-04	232.7	2.34E-02	1.41E-08
Ag	2.19E-05	70.2	6.70E-04	7.44E-11
Zn	2.44E-04	339.2	7.46E-02	9.24E-08
Pb	1.05E-04	232.8	2.06E-02	1.09E-08
Cu	4.65E-05	134.2	4.48E-03	1.06E-09
Cr	1.80E-04	544.3	9.18E-02	8.39E-08
Fe	9.56E-03	376.4	3.36E+00	1.63E-04
Alcohol	2.93E-05	3128.5	9.06E-02	1.35E-08
P	2.54E-02	869.7	21.6E+00	2.78E-03
Detergent	2.46E-02	74.9	1.30E+00	1.62E-04
Hg	2.00E-07	115.9	1.00E-05	9.07E-15
Overall	1.00E+00		7.80E+02	1.05E+00

Table 5. Exergy of the dewatering sludge

Components	x_i (molmol^{-1})	Specific chemical exergy (kJmol^{-1})	Total molar chemical exergy (kJmol^{-1})	Specific chemical exergy (kJL^{-1})
COD	1.70E-01	2720.0	4.61E+02	7.96E+01
Cd	9.40E-05	293.5	2.61E-02	2.55E-06
Ni	1.67E-03	232.7	3.61E-02	6.12E-04
Ag	2.19E-04	70.2	1.08E-02	2.40E-06
Zn	1.36E-02	339.2	4.47E+00	6.19E-02
Pb	1.66E-03	232.8	3.60E-01	6.06E-04
Cu	4.01E-03	134.2	4.83E-01	1.97E-03
Cr	2.12E-03	544.3	1.12E+00	2.43E-03
Fe	8.07E-01	376.4	3.03E+02	2.49E+02
Hg	2.34E-07	115.9	1.80E-05	4.35E-12
Overall	1.00E+00		7.71E+02	3.28E+02

In Table 6 are summarized the values of the input, output, destroyed and lost exergy flowrate/rate for the studied Wastewater Treatment Process.

Table 6. Values of the input, output, destroyed and lost exergy flows for the studied Wastewater Treatment Processes

	Exergy rate/flowrate		
Process	Input (kW)	Output (kW)	Destroyed and lost (kW)
Cañaveralejo WTP	10258.90	4040.00	6218.90

A detailed description of exergy calculations are showed in Mora (2009). In Fig. 2 is presented the exergy balance for the Cañaveralejo Wastewater Treatment Process.

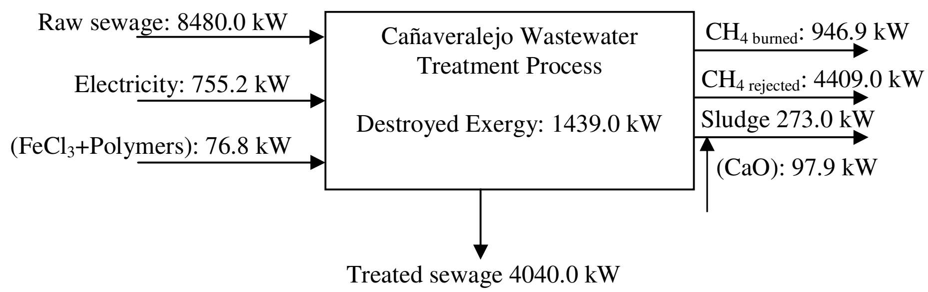

Figure 2. Exergy balance of Cañaveralejo WTP

In Table 7 are presented the values of the calculated exergy indexes based on the results of the exergy balance. These indexes were used in the evaluation of the environmental performance and renewability of the Wastewater Treatment Process.

Table 7. Environmental exergy efficiency and renewability index of the analyzed Wastewater Treatment Process

	Exergy index	
Process	$\eta_{env,exerg}$	λ
Cañaveralejo WTP	0.394	0.770

As it can be seen from Table 7, for the chemically enhanced primary treatment the indexes are acceptable, although indicating that the exergy performance can be improved, mainly because part of the generated methane is used to produce electricity.

Aiming at improving the exergy performance of the processes, Table 8 presents the exergy indexes in a scenario where the processes wastes exergy (produced gas and dewatering sludge) are not destroyed. For instance, if all the methane is used as fuel in an internal combustion engine with 30% thermal efficiency and sludge exergy was used for methanol production, as proposed by Ptasinski *et al.*, 2002. In doing that, the values of the indexes increase significantly, as shown in Table 8.

Table 8. Environmental exergy efficiency and renewability index of the analyzed Wastewater Treatment Process considering the use of the produced gas and dehydrated mud

	Exergy index	
Process	$\eta_{env,exerg}$	λ
Cañaveralejo WTP	0.673	4.200

For the methanol production the sludge goes through a gasification process which produces tar and a gas which serves as input to methanol process, this process is complex and high cost. Another technique for sewage sludge treatment is fermentation, which produces a gas rich in methane that can be used to generate electricity and a digested sludge with a very low calorific value. The incineration of sludge depends of sludge calorific value. Finally the sludge of sewage can be used as fertilizer, if the percentage of heavy metals is very low and are observed nutrients in its composition.

Comparing the environmental exergy efficiency used in this work with the definition of exergy efficiency for sewage treatment plants given by Gallegos-Muñoz et al. (2003), it was observed that their definition is focused on the effect of the exergy destruction realized by treatment process and the percentage that represents this effect on electrical and mechanical consumption. The environmental exergy efficiency, defined here specifically seal the use of sewage exergy, through recycling of treated sewage and its by-products exergy (biogas and dewatering mud).

The value obtained for the renewability exergy index (λ) greater than 1 (see Table 8), mean that the exergy of the products of sewage treatment system (WTP Cañaveralejo), could be used to restore the previous environmental conditions and still have a flow of positive exergy for another purpose.

The restoration of the environment in this case can be related to the production of electricity from the produced biogas, which replace the effect that caused on the environment the power network electricity consumption by the process, and the excess positive exergy flow can be represented by an excess of produced electricity and by the use exergy of dewatering mud for agricultural purposes or still as an input in the methanol production.

4. CONCLUSION

The exergoecology analysis, supplemented with the exergy indexes, is a scientific methodology with well defined criteria to assess and quantify the environmental performance of sewage treatment processes on a single basis: the exergy concept. With the application of this methodology it is possible to compare and characterize the environmental exergy performance and renewability of WWT processes.

The environmental exergy efficiency is a suitable indicator for ecological evaluation because it presents a unified thermodynamic measure for objectively evaluating resources utilization, quality of energy conversion processes and environment impact. This relation must be used for determining the most energy efficient system among various chemical and biological wastewater treatment processes.

The environmental exergy efficiency identifies the technical inefficiencies in the conversion of organic matter in sewage flows, and highlights clearly that the technology used to utilize the organic matter in sewage is far from being optimized. This is because the technical solutions have not considered the recovery of exergy from organic matter as an important aspect. According to Hellström (2003), if a urine separation system was included in the wastewater treatment plant, the nutrients exergy recovery could be improved with a consequent increase of the environmental exergy efficiency.

That is, environmental performance is better as greater is the potential for recovery the by-products of the process. The value of renewability exergy index (λ) greater than 1 means that the products exergy of Cañaveralejo WTP could be used to restore the previous environmental conditions and still have a flow of positive exergy for another use.

The renewability exergy index is a complement good to environmental exergy efficiency as takes into consideration, besides the exergy destruction, the non-renewable exergy sources used by the process.

As the values of the exergy indexes are influenced by the definition of the boundaries of the considered control volume, it is important to observe the size and compatibility of the control volumes in order to avoid distortions in a comparative analysis.

Finally, from these results it is concluded that the proposed exergy indexes are useful in evaluating and comparing the environmental performance of sewage treatment technologies, from an efficiency and renewability viewpoint.

To complement this work, it is proposed to include a thermoeconomic analysis in the presented methodology.

5. ACKNOWLEDGEMENTS

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