On an Exergy Efficiency Definition of a Wastewater Treatment Plant

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Abstract

The first part of the paper analyzes the degradation of the water of a river in terms of its exergy while passing through the urban zone of a city. This analysis describes and compares the degradation process of the river from point to point, so it can be used to unify all the water quality measurements into the same exergy units [kJ/kg]. The second part introduces an exergy efficiency for a wastewater treatment plant that proposes to unify the means to measure the efficiency of the water treatment plants and their sub-systems. This particular case of study concerns the Lerma River in Mexico, which runs through Salamanca City, by determining its exergy at five sampling points.

Key words: exergy efficiency, degradation process, wastewater treatment plant

1. Introduction

As is well known, the exergy method (Szargut et al., 1988) can be associated with its exergy components: *mechanical, thermal, potential, kinetic and chemical.* The exergy values are helpful for comparing the quality and quantity aspects of the water of the river at the different sites, thereby obtaining a wider understanding of the degradation process of the river. In a previous work (Zaleta et al., 1996), the exergy method was applied to the water of a river at different sites of the same, and the mass flow and the measure of five parameters: pressure, temperature, altitude, velocity and chemical composition were also obtained. This exergy application shows the "Thermodynamic Availability of the River's Water". The exergy method could be a tool to determine the quality [kJ/kg] and the quantity [kW] of the river water availability at different locations. Urban population and industries in Mexico are the main areas responsible for the huge production of waste products and pollutants that affect, directly and indirectly, the rivers. The Lerma River runs through Salamanca City in Mexico, and the pollution of this river is extremely critical since a large inhabitant area and local industries that discharge pollutants into the river are there. Furthermore, the over exploitation of this resource by agricultural activity (seasonal activity) increases steadily each year, reducing the water flow and provoking an increase in the pollution concentration.

Therefore, it is necessary to improve the conditions of the river through treatment processes. According to the actual conditions of the Lerma River, a specific commission of the government is exploring the feasibility of building up a treatment plant alongside the Lerma's basin. One of the purposes of this work is to develop a general criterion underpinned by

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exergy concepts for establishing such a treatment plant.

The exergy analysis is a technical method for diagnosing, evaluating and optimizing energy processes. The exergy study has been typically applied to power plants (Bejan et al., 1996; Kotas, 1985) where the opportunities of energy saving are identified. However, the study has been extended to analyze process plants and natural resources (Brodyansky et al., 1994; Gaggioli, 1980) where the exergy balance is an important factor to meet the energy demand in each component of the plant as well as its relationship with the energy cost.

On the other hand, indexes or standards to evaluate the behavior of wastewater treatment plants can be widely varied. In this sense, exergy may play a fundamental role in unifying the criteria of evaluation of wastewater treatment plants. The efficiency model (see Appendix I) that is set in this paper is:

$$\varepsilon = \frac{B_{NTW} - B_{TW}}{B_R} \qquad (1)$$

which is the ratio of the difference between the

non-treated water exergy (B_{NTW}) and the treated water exergy (B_{TW}), to the resources exergy (B_R) (electrical and mechanical consumptions of the plant).

2. Exergy Method Applied to a River

The availability of a renewable resource can be understood as "its accessibility". In order to avail a resource it is necessary to make chemical and physical changes until it is obtained in the conditions required for its use (for example, for human consumption, water must be extracted from a river, purified, and distributed to the end users). The analogy between the concept of availability of a natural resource and the concept of exergy enables to relate each of the parameters that characterize a natural resource to the exergy components. The "availability" of the water of a river can be expressed in terms of the temperature, pressure, height, velocity, and composition, and assuming the approach of an incompressible liquid and dilute substances (valid for the case of the water of a river), it is possible to calculate the exergy with the equation (2).

$$b_{a,o}\left[\frac{kJ}{kg}\right] = C_{p,H_2O}\left[T_a - T_o - T_o \ln(\frac{T_a}{T_o})\right] + v_{H_2O}(P_a - P_o) + \Sigma x_{i,a}(\mu_{i,a} - \mu_{i,o}) + \frac{1}{2}(c_a^2) + g(z_a - z_o) \qquad (2)$$

$$Exergy = \qquad Thermal \qquad\qquad Mechanical \quad Chemical \quad Kinetic \quad Potential$$

A Stable Reference Environment (SRE), which is defined through supposed values (say, ambient, T_0, p_0, c_0 and z_0), conditions the exergy method. It is convenient to use the SRE proposed by Szargut et al. (1988), since it reproduces the most similar conditions of the actual environment of the Earth. According to equation (2), the *thermal exergy component* depends on both the heat capacity of the aqueous solution and its absolute temperature. The *mechanical exergy component* is calculated from the specific volume of the water solution and from the pressure difference between the river and the SRE. The specific heat capacity, c_p, and the specific volume, *v*, of the solution can be estimated without significant errors, if both are considered as properties of pure water (Perry and Chilton, 1997). In order to evaluate the *potential exergy component,* it is necessary to have the altitudes z with respect to the sea level. This component is important for calculating the maximum mechanical work that may be obtained from a waterfall, as in a hydroelectric plant. The *kinetic exergy com-ponent* is of relatively little importance in comparison with other exergy components. In order to evaluate it, it is

necessary to determine its mean velocity, which depends on the flow and the amount of water. The *chemical exergy component* is the most complex to be calculated; this component may be broken into the following components: *i) the chemical exergy of pure water, ii) the chemical exergy of the dissolved inorganic substances, iii) the chemical exergy of the organic substances.*

2.1 Chemical exergy of the water in the river

The component regarding the chemical exergy of the pure water (H_2O) provides information about its thermodynamic degradation. In other words, it is the availability of the pure water at different environmental conditions along with other substances (salts, organic, etc.). The magnitude of this exergy component can be evaluated as a pure substance in a solution by means of its activity a_i, that is:

$$b_{q,i} = x_i\left(\mu_i - \mu_{i,o}\right) = x_i RT_o \ln\left(\frac{a_i}{a_{i,o}}\right)\Bigg|_{i=H_2O} \qquad (3)$$

where a_{H2O} and $a_{H2O,o}$ can be estimated from the measurement of the colligative properties, such as osmotic pressure, π.

$$\pi_{H_2O} = -\frac{RT_o}{v} Ln\left(a_{H_2O}\right)$$

(4)

$$\pi_{H_2O,o} = -\frac{RT_o}{v} Ln\left(a_{H_2O,o}\right)$$

This osmotic pressure can be obtained by measuring the electrical conductivity of the river's water (Diaz and Roig, 1978), assuming that the osmotic pressure is a function of the concentration of salts present in the solution (there are not important errors in the case of very diluted substances, such as the water of a river) (ASME 1989).

2.2 Chemical exergy of the dissolved inorganic substances

The chemical exergy of the dissolved inorganic substances is determined with the well known procedure for an electrolytic solution, where the activity a_i for each chemical substance present in the river water and also in the SRE can be expressed in terms of the activity coefficient γ, and its molality, m:

$$a_i = \gamma_i m_i$$

(5)

The activity coefficient, γ, of each one of *the electrolytic species* can be determined by means of the equation obtained by Debye-Hückel (Díaz and Roig, 1978). The activity coefficient of *non-electrolytic inorganic substances* is always $\gamma=1$.

2.3 The chemical exergy of organic substances

The chemical exergy of organic substances represents a difficult problem due to the diversity of species involved when it comes to determining the organic substances present in the river's water. However, organic substances are not present in the SRE according to Szargut's definition (Szargut 1989). In this sense, the processes of self-purification of organic substances take place naturally in rivers. This means that the oxygen dissolved in water, which comes either from the photosynthesis of the plants or from the atmosphere, acts as an oxidant for the organic substances present; this process may be slow or fast, depending on the type of substances, but it is well known that the final product of the oxidation is CO_2, etc. In thermodynamic terms, one way of quantifying the exergy content of organic substances is by proposing a single organic molecule to represent the *"mean organic substance"*.

For a practical analysis of the river, a representative substance such as a fat molecule is proposed, as is shown in equation (6). This allows estimating the order of magnitude of the exergy of the organics components:

$$C_{39}H_{80}O_3 + \frac{115}{2}O_2 \leftrightarrow 39CO_2 + 40H_2O \quad (6)$$
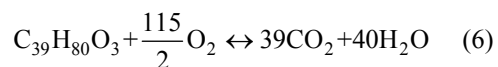
By means of laboratory measurements of the "Chemical Oxygen Demand", COD, the mg. of O_2/lt of river water consumed in the reaction is estimated, thereby obtaining the amount of moles of mean organic substance per lt. of water. The exergy of the organic substance should be obtained from the definition of exergy reaction in standard state (Sussman 1980, Ikumi et al. 1982, Lloyd and Davenport 1980), according to the expression:

$$b_{org}{}^o = \Delta h_f^o - T^o s^o - \sum x_j \mu_j^o \qquad (7)$$

where Δh_f^o, s^0, μ^0 are known for industrial substances (ASME 1989).

3. Case of study

The water of the Lerma River was evaluated in exergy terms at different sampling sites. Figure 1 shows the location of the Lerma River, while the composition at different sampling sites of the river water are shown in TABLES I and II.
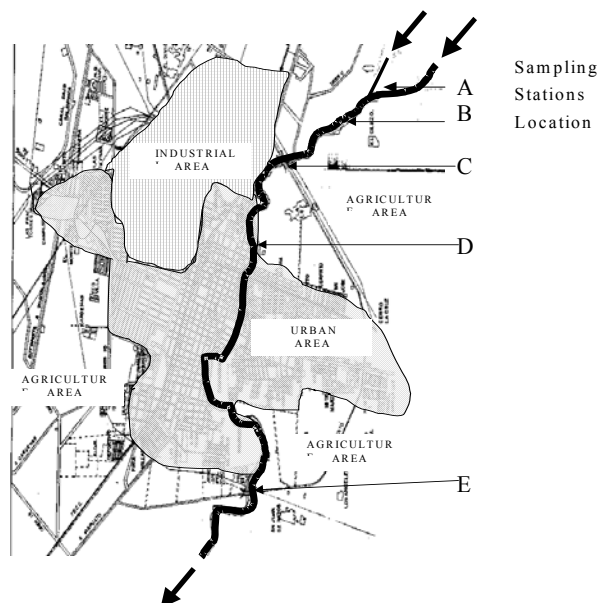

Figure 1. Sampling sites along the Lerma River at Salamanca City

TABLE I. WATER COMPOSITION IN THE SAMPLING SITES ALONG THE LERMA RIVER.

Sampling Site	Chloride-residues	Sulphates	Bicarbonates	DQO	Chlorides	Sodium
A	2.82e-6	5.43e-4	2.4e-3	7.6e-3	2.1e-3	2.1e-3
B	2.82e-6	1.11e-3	1.19e-3	4.2e-e	1.4e-3	1.8e-3
C	2.82e-6	8.58e-4	1.5e-3	4.8e-3	1.4e-3	1.6e-3
D	2.82e-6	1.67e-3	9.8e-4	7.8e-3	2.5e-3	3.1e-3
E	2.82e-6	2.27e-3	1.6e-3	6.7e-3	2.6e-3	4.1e-3

TABLE II. DATA OF THE WATER IN THE SAMPLING SITES ALONG THE LERMA RIVER.

Sampling Site	T (°C)	Ph	% O_2	Conductivity (µs)	TDS (mg/lt.)
A	19	7.0	2.2	550	276
B	22	7.13	2.2	389	194
C	21	7.0	2.0	405	202
D	22	6.95	1.2	450	225
E	23	7.21	1.8	488	243

Note:

DQO   Chemical oxygen demand

TDS   Total Dissolved Solids (Total filterable residue)

3.1 Exergy efficiency for a water treatment plant

The exergy analysis of the plant considers two important aspects:

1) the exergy calculation at the inlet and outlet conditions of the main sub-systems of the plant, and
2) the cost balance of the system.

The first one defines the exergy values according to the aforementioned method, and the second one relates the investment, operation and maintenance costs. The cost analysis can be calculated by typical methods of process evaluation. As it has to do with a process with one product there is no problem of cost allocation in multiproduct processes. The unit costs of the water streams of the plant can be determined by using the thermoeconomic procedures (Lazzaretto, A. and Tsatsaronis, G., 1996; Lozano and Valero, 1993).

The proposed wastewater treatment plant consists of:

1) a preliminary filtering of the incoming water flow,
2) an anaerobic treatment process,
3) a filtration process, and
4) at the end, chlorine gas is used to disinfect the water flow

Figure 2 shows a scheme of the wastewater treatment plant. The wastewater is received in the *regulator tank* (I) from the principal receiver tank; the water is then pumped at a constant flow straight to the *biological reactor* (II) where it is mixed with air. The water from the reactor runs to the *clarificator* (III) by means of gravity, where the residual sludges are gathered and sent to the *receiver tank* (IV). The water passes by gravity to *the filters* (V) from the clarification tank, more residual sludge is removed therein, while an automatic valve and *level indicator* (VI) control the flow to the *tank* (VII), where finally the chlorine gas is injected to disinfect the water. The residual sludges are collected in the *digestor* (VIII) and sent to the *tank* (IX) and then to the *filters* (X), in order to be dried out.
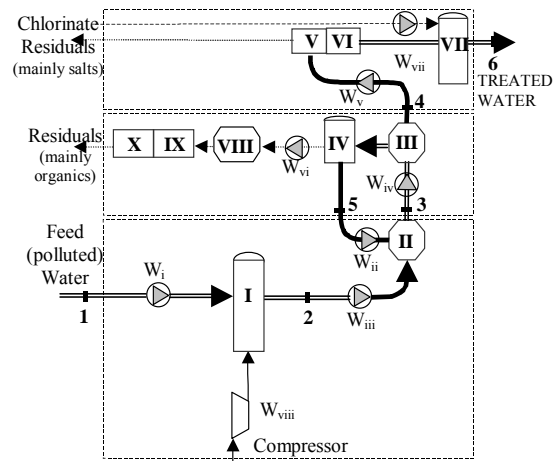
Main Components	Main Streams
I) *Regulator tank*	1) *Feed water*
II) *Biological reactor*	2) *Regulated water*
III) *Clarifier water*	3) *Clarified water*
IV) *Receiver tank*	4) *Water to filters*
V) *Filters*	5) *Recycled water*
VI) *Level indicator*	6) *End treated water*
VII) *Chlorine water*	**Power Requirements**
VIII) *Digestor*	$W_{i,ii,iii,iv,vi,vii}$ *Pumps*
IX) *Tank residual sludge*	W_v *Motors*
X) *Filters*	W_{viii} Compressor

Figure 2. Scheme of the functional structure of the Urban Wastewater Treatment Plant (PEMEX, 2000).

The physical-chemical characteristics of Lerma's water permit the proposal of an anaerobic process as adequate treatment where the water obtained, according to its quality, can be used in industrial processes and agricultural activities.

The main sub-systems of the pilot plant may be broken up into three (Λ_1, Λ_2 and Λ_3 respectively), as represented in Figure 3.
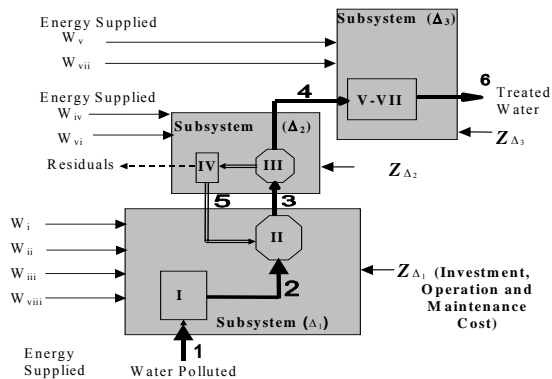

Figure 3. Main sub-systems of the Waste-water Treatment Plant.

In each sub-system the inlet and outlet exergy streams were evaluated (TABLES III, IV and V). Moreover, the exergy efficiency in each of the three sub-systems is determined by the proposed definition, equation (1).

In the whole plant, the products are represented as the exergy of the outgoing water, and the fuels are represented as the exergy supplied as electrical energy used in each subsystem. TABLE III shows the values of the energy supplied to the components of each sub-system. By applying the definition of equation

(1) to each sub-system (see Appendix I), it is possible to write:

$$\varepsilon_{\Lambda_1} = \frac{(B_1 + B_5) - B_3}{W_I + W_{II} + W_{III} + W_{VIII}} \qquad (8a)$$

$$\varepsilon_{\Lambda 2} = \frac{(B_3 - B_5) - B_4}{W_{IV} + W_{VI}} \qquad (8b)$$

$$\varepsilon_{\Lambda 3} = \frac{B_4 - B_6}{W_V + W_{VII}} \qquad (8c)$$

$$\varepsilon_{total} = \frac{B_1 - B_6}{W_{total}} \qquad (8d)$$

4. Results

The chemical composition of the water streams in the plant was determined through field measurement data of the *electrical conductivity, Ph, TDS (Total Dissolved Solids)* and *Oxygen Chemical Demand.* According to the parameters measured at the input and output streams of the sub-system, and applying equations (1)-(3), the total exergy, efficiencies, and costs values were evaluated. These results are shown in TABLES IV and V.

Respective treatment costs were obtained by using typical cost accounting, for each sampling site along the river at different dates, as shown in Figure 4 and Figure 5. In Figure 4, the costs are related with the volumetric flow, while in Figure 5 the costs are related with time at each site. The costs are obtained by considering constant the exergy efficiencies of each sub-system of the plant proposed for the treatment of the Lerma's water. The costs include the investment, operation and maintenance costs of the plant.
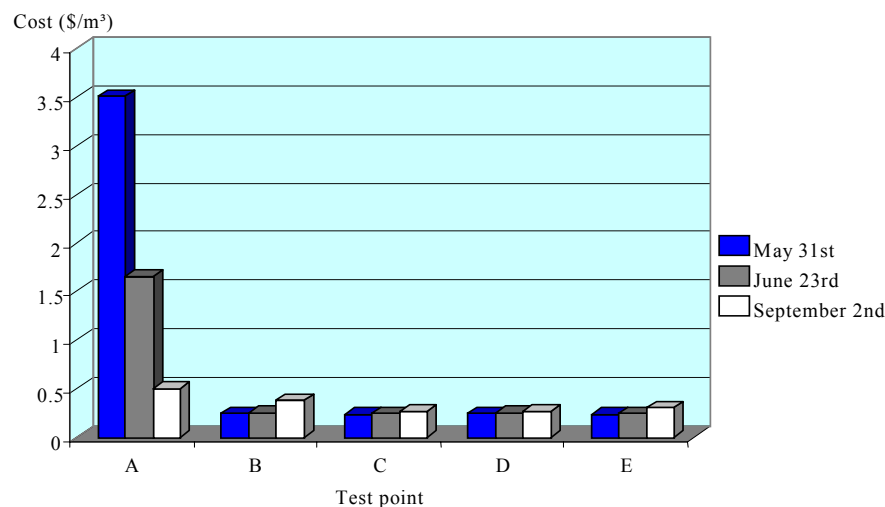

Figure 4. Costs according to the volumetric flow in each test site alongside the Lerma River.
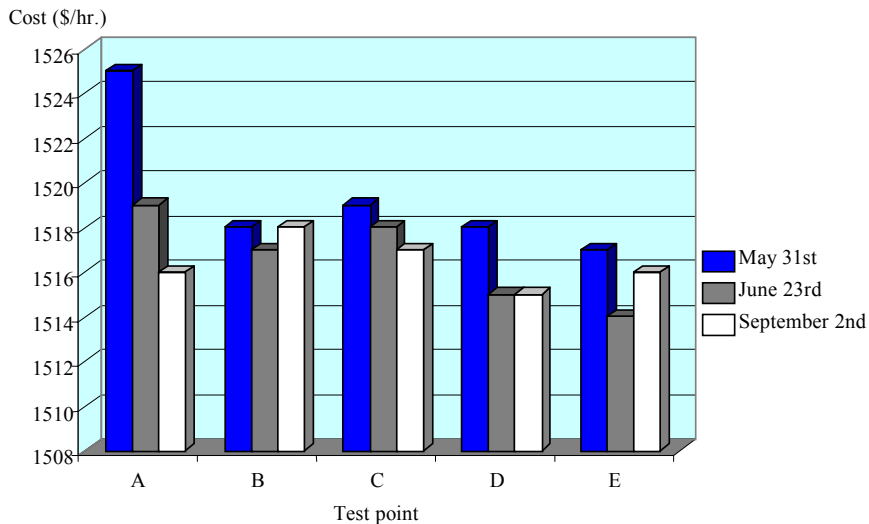
Figure 5. Treatment costs in each test site alongside the Lerma River.

5. Conclusions

In agreement with the results of TABLES IV and V, the exergy efficiency of sub-systems Δ_1 and Δ_2 is lower with respect to sub-system Δ_3. This must be due to the fact that in these systems an oxidation of organic substances occurs with a high consumption of mechanical power, and in subsystem Δ_3 a separation of solids and salts occurs with a lower amount of mechanical work. In these terms, the exergy efficiency can serve to compare water treatment plants (or subsystems) or to diagnose in time the behavior of a same system.

The analysis of the pilot plant (refer to Figure 3, TABLE IV), on the other hand, permits the identification of the highest specific cost ($/kJ) at point 6, and the highest total cost ($/hr) all the way through the process at point 3. The cost at point 6 represents the final cost needed to obtain the water quality required for industrial and agricultural activities. The cost obtained involves all capital and energy requirements to produce clean water in the plant. It is observed that if the water quality required increases, then the specific cost will increase. The total cost at point 3 of the plant depends upon the exergy efficiency of sub-system 1 (biological reactor), in this case the lowest efficiency in the plant. It is in this sub-system where the energy saving opportunities in the plant seem to be, but it depends on the technological limitations of the process of the sub-system.

The treatment cost of the Lerma River water depends on its quality and quantity conditions, and according to the results obtained, the highest volumetric cost occurs at the sampling station A. Insofar as there exists a low volumetric flow with high investment, operation and maintenance costs, it means that an over sizing of the plant exists at this point.

On the other hand, the criteria concerned with the specific exergy of the water depends on the pollution degree (or specific exergy). This is, when the specific exergy is high (high pollution degree), at sampling site A, on May 31st and June 23rd, or sampling site B, on September 2nd, the energy requirements of the plant for the treatment process increase at this site, so the total cost increases. In our case, we propose a plant with similar characteristics to that located in site B, because the volumetric flow is higher than the volumetric flow in site A, thus reducing the total cost of the plant. One criterion to select the right location of the treatment plant could be to pick out those sites showing a minimum treatment cost and the maximum volumetric flow.

Nevertheless, in a realistic scenario, a wastewater plant should be located near a system for collecting all (or most) polluted water produced in the city, or at an outlet of the city, once all the polluted water has been collected.

TABLE III. EXERGY REQUIREMENTS OF THE PILOT PLANT FOR TREATMENT OF URBAN WASTE WATER

SUBSYSTEM	REQUIREMENT	DESCRIPTION	ENERGY SUPPLY (kW)
Λ_1	W_i	Pump	32.25
	W_{ii}	Pump	32.25
	W_{iii}	Pump	32.25
	W_{viii}	Compressors	161
Λ_2	W_{iv}	Pump	32.25
	W_{vi}	Pump	11
Λ_3	W_v	Motor	50
	W_{vi}	Pump	11

TABLE IV. PARAMETERS OF THE STREAMS, TOTAL EXERGY AND COSTS IN EACH POINT OF THE PILOT PLANT.

Parameter \ Stream	1	3	4	5	6
Position* (m)	1710	1710	1710	1710	1710
Volumetric Flow (m^3/s)	0.086	0.113	0.086	0.027	0.086
Pressure (atm)	1.73	1.87	1.48	1.38	1.37
Temperature (K)	298	298	298	298	298
Velocity (m/s)	0.42	0.38	0.19	0.53	0.19
Total Stream Exergy (kW)	389.706	513.98	387.30	125.30	373.50
Unit Stream Cost ($/kJ)	0.0	9.8×10^{-4}	9.9×10^{-4}	9.9×10^{-4}	1.03×10^{-3}
Total Stream Cost ($/hr.)	0.0	1812.8	1382.9	433.8	1383.3

* the position with respect to sea level.

TABLE V5. EXERGIES AND EFFICIENCY IN EACH SUB-SYSTEM OF THE PILOT PLANT.

SUB-SYSTEM	Δ_1	Δ_2	Δ_3	Total
Product Exergy, B_P (kW)	1.017	1.3	13.8	16.117
Requirement Exergy, B_F (kW)	258.5	43.25	61	362.75
Efficiency, ε (%)	0.3934	3.0058	22.6229	4.443

APPENDIX I

The exergy efficiency of a water treatment (sub-) system can be defined from its exergy balance. Figure 6, for instance, shows an adiabatic steady-state control volume which receives as input: mass flows ($\Sigma m_i * b_{inlet}$) and mechanical power ($\Sigma W_{shaft\ work}$); and as output: mass flows ($\Sigma m_j * b_{outlet}$), irreversibilities (internal and heat loss to environment), as well as losses due to the mass flows ($\Sigma m_l * b_{loss}$); that can be expressed as:

$$0 = \sum \dot{m}_j b_{outlet,j} - \sum \dot{m}_i b_{inlet,i} - \sum \dot{W}_{shaftwork} + \sum \dot{m}_k b_{loss} + \sum \dot{Irrv}$$

Alongside the water treatment processes a loss of organic substances (oxidation, separation, etc.) and inorganic substances (inverse osmosis, etc.) occurs. It causes the exergy of the outlet water streams to be less than at the inlet. In other words, the exergy of the water once treated is less than at the inlet conditions;, further there

exists a consumption of mechanical work so as to reach this "productive objective". Hence, **the exergy efficiency (ε)** is defined as the deterioration of the exergy [kW] of the inlet streams according to the outlet conditions ($\Sigma m_i * b_{inlet} - \Sigma m_j * b_{outlet}$), per unit of power consumed ($\Sigma W_{shaft\ work}$) [kW].

Likewise, from the exergy balance, the value **(1+ε)** as index of the exergy destruction and losses per unit of work consumed throughout can be defined, as expressed below:

$$\varepsilon = \frac{\sum \dot{m}_i b_{inlet,i} - \sum \dot{m}_j b_{outlet,j}}{\sum \dot{W}_{shaftwork}} = \frac{\sum \dot{m}_k b_{lost} + \sum \dot{Irrv}}{\sum \dot{W}_{shaftwork}} - 1$$
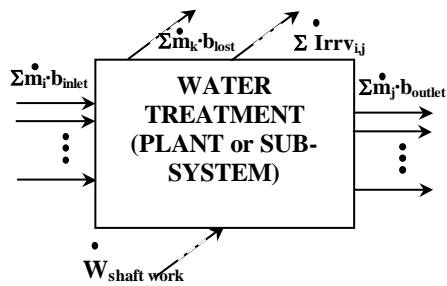
Figure 6. Control Volume of a Water Treatment Plant

Nomenclature

a	Chemical activity
b	Specific exergy
B	Exergy
C	Specific heat
c	Flow velocity
h	Specific enthalpy
g	gravity
m	molality
P	Pressure
s	specific entropy
T	Temperature
v	Volume
x	Molar fraction
z	Height

Greek

Δ	Difference
ε	Exergy efficiency
η	Efficiency
Λ	Sub-system
γ	Activity coefficient
μ	Chemical potential
π	Osmotic pressure

Subscripts

A	Actual conditions
i	Substances
F	Resources (Fuels)
NTW	Non-treated water
o	Ambient conditions
P	Products
R	Resources of the process
TW	Treated water

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