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Exergy costs analysis of water desalination and purification techniques by transfer functions

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ABSTRACT

The unit exergy costs of desalination and purification, which are two alternatives commonly used for water supply and treatment, have been characterized as a function of the energy efficiency of the process by combining the Exergy Cost Analysis with Transfer Function Analysis. An equation to assess the exergy costs of these alternatives is then proposed as a quick guide to know the energy efficiency of any water treatment process under different design and operating conditions. This combination, was satisfactory applied to groundwaters and water transfers. After identifying the boundaries of the system, input and output flows are calculated in exergy values. Next, different examples are analyzed in order to propose a generic equation to assess the exergy cost of the water restoration technologies, attending to their main features. Recovery ratio, energy requirements and salts concentrations (for desalination), and plant capacity and organic matter recovery (for water purification) are introduced in the calculations as their main endogenous parameters. Values obtained for typical operation ranges of commercial plants showed that unit exergy costs of water purification ranged from 3.3 to 6.8; maximum values, as expected, were found at low plant capacities and high organic matter removal ratios. For water desalination, values varied from 2 to 7 in membrane technologies and from 10 to 26 in thermal processes. The recovery ratio and salts concentration in raw water increased the unit exergy costs in membrane techniques. In distillation processes, the unit exergy cost increased as the quality of the heat supplied did, but they are not so sensible to seawater salinity.

1. Introduction

The optimization of water supply and treatment technologies is an important open issue of research. Several studies focused on the optimization of operation costs of wastewater treatment plants (WWTP) by energy consumption reduction [1], and also by energy consumption minimization together with environmental criteria such as the minimization of greenhouse emissions [2,3] and resources consumption, emissions and residues minimization in water purification processes [4,5], by applying environmental evaluation tools [6,7] or by using optimization economic models [8,9]. Focusing on water supply, and specifically to desalination, several studies [10–13] aimed to the optimization of operation and design parameters in specific desalination plants.

In the context of energy efficiency, exergy analysis has been usually applied to thermal processes integration and optimization. It focusses in the Exergy Efficiency assessment as the ratio between the exergy of the obtained products and the exergy of the demanded resources [14–18]. Exergy is gradually destroyed due to the unavoidable irreversibilities produced along the productive chain, or process. Examples of exergy analysis in complex energy systems are cement plants [19], geothermal plants [20,21], combined cycle power plants [22], solar energy systems [23,24], and other systems keeping always in mind the variation of their main operation parameters [25–28]. Meanwhile, as exergy evaluates the energy quality of resources and products, their use in desalination and water depuration includes the analysis of the useful energy of some by-products of these plants like brines and sludge.

Energy efficiency (i.e. exergy) is connected with economy within the thermoeconomy theory. It applies the Laws of Thermodynamics and translates energy degradation into economic costs thereby leading to an economic theory. That is, a combined analysis applying the 2nd Law allow knowing the monetary value of the exergy flows and the streams of materials and their increase with the exergy lost. Thus, the concepts of productivity, efficiency, costs and benefits can be objectively stablished and calculated.

In water issues, thermoeconomics was applied to different scopes: from specific water treatment processes [29] to the management of river watersheds in accordance with Water Framework

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Nomenclature

a	activity (mole/kg)
b	specific exergy (kJ/kg water)
B	exergy (kW h)
BD	Brine blowdown
C	concentration (ppm) or conductivity (μS/cm)
C_{p,H_2O}	specific heat of pure water (kJ/kg K)
COD	chemical oxigen demand (ppm)
CW	cooling water
D	distillate/permeate
ED	electro-dialysis
F	fuel
h	altitude (m)
k^*	unit exergy cost
LCA	life cycle assessment
MSF	multi-stage flash distillation
MED	multi-effect distillation
P	product
R	ideal gas constant (J/mol K)
Rc	recovery ratio (desalination)
RE	reference environment
RO	reverse osmosis
Rr_{OM}	organic matter recovery
SW	sea water
T	temperature (K)
TF	transfer function
TOC	total organic carbon (ppm)
$WWTP$	water-water treatment plant
x	molar x: concentration (mole/l)
ΔB^*	total exergy costs (kW h)

Subscripts and superscripts

ch	chemical
deg	degraded water state
t	thermal desalination
m	membrane desalination
i	substance i
IM	inorganic matter
OM	organic matter
o	reference
p	potential
$Proc$	process
$Prod$	product
Q	plant capacity (m^3/s)
$Rest$	restored water state
in	salts concentration in raw water
out	salts concentration in the permeate

Directive in Europe [30–32]. Energy consumption and degradation are considered in the estimation of cost of the supply alternatives, as well as in the assessment of the value of water resources through the concept of reposition cost.

For instance, in water treatment processes, a thermoeconomic methodology based on exergoeconomic relations was provided by Abusoglu et al. [33] to allocate the cost of the flows through subcomponents of some real wastewater treatment plants (WWTPs). Other authors such as Khosravi et al. [34] focused the research on the estimation of environmental resources degradation in specific WWTPs within environmental indexes focused on the assessment of exergy efficiency and pollutions rates in order to quantify environmental impacts. Concerning the exergy analysis of water supply technologies, and specifically desalination, published works were focused on exergy losses and irreversibilities in diverse seawater desalination units [35–37], including separately distillation units [38,39] and reverse osmosis (RO) units [40].

Monetary costs of RO according to those authors are around 0.5–1 €/m^3. Those works showed a great variability among values of exergy efficiency and energy consumption, depending on the type of process, plant capacity and salty water composition. Values of exergy efficiency found in literature are usually higher in RO systems, and varied in a wide range from 6% [39] to 30% [36]. Its low value is mainly due to two reasons. First, the pressure applied to the RO modules tends to be twice the theoretical minimum. Second, brine produced has also a significant exergy amount, but energy recovery of this flow is not well developed yet. In distillation systems, that efficiency is even lower (from 3–6% [36] to 10% [38]) taking into account that desalination is obtained by total evaporation of seawater. Values of exergy efficiency in wastewater treatment plants found in literature [33,34] are around the 30%, being the exergy content of the sludge one of the major contributions of that reduced value.

In the search of the cost from the physics of any system, the exergy expense through the energy conversion process was studied by Valero et al. in [41] through the unit exergy cost concept. In this way, exergy efficiency of the process is measured in economic terms, therefore being useful for plant management. In connection to this, the general theory of exergy cost [42] defined the irreversibility in a system as the difference between the exergy of demanded fuels and desired products. The unit exergy cost (k^*) was defined there by the inverse of the exergy efficiency, as the ratio between the exergy needed to produce a resource (fuel, F) and the exergy of the resource on which the interest is focused (product, P). From typical operating parameters of main water treatment (purification) and commercial desalination technologies, the corresponding unit exergy costs were obtained in a previous work [29]. The application of this methodology leads to costs according to the expected values given by the conventional analysis. Nevertheless, it includes additional information coming from the energy efficiency of the involved processes as well as the usefulness of the byproducts produced in that process.

Previous research in the field of unit exergy costs of water technologies [29] stated the need of having a generic expression to estimate that cost for any kind of water treatment processes. Recently, the application of a new methodology to obtain those unit exergy costs [43] by the help of TF analysis gave significant advantages. In that first attempt, the use of water transfers and groundwaters, and their effect in the mixing with available resource waters was studied in depth. As it is explained in detail in Section 2, the estimation was performed as a function of design and operation parameters of that alternatives. Of course the methodology can be extended to a wide range of alternatives to meet water demands. The exergy costs of desalination (by using thermal and membrane techniques) and waste water treatment technologies, are now estimated. Then, a wider range of applications is achieved. Apart from this, it is possible to compare the energy efficiency of different water supply alternatives, which are not easily evaluable within a conventional energy analysis, by a generic equation that includes the main design and operation parameters of each alternative.

Note that exergy cost calculations include not only energy issues but also chemical concerns about water quality or recovery