Application of the Exergy Method to the Environmental Impact Analysis: A Case Study

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Abstract. The cumulative exergy method is used to analyze and optimize a heat pump distillation process with respect to the total environmental impact including resource use and emissions. The results from the proposed method are compared with the ones from thermoeconomics. It is found that such an extended exergy analysis offers a new insight and permits the identification of solutions which are more stable in time and independently of economic conditions.

Introduction

The increasing concern for the environmental impacts of human activities has stimulated the development of new methods for the analysis of industrial processes and the implementation of natural resource measures. Nowadays there are several tools for design or analysis of environmental objectives of industrial processes. Herein, a well established and comprehensive approach is the life cycle assessment (LCA). LCA has undeniable merits but, being essentially a first-law type of analysis, its validity is tainted by its inability to account for different types of energy carriers [1].

Various approaches have been proposed and developed in the last years with the intention to obtain environmental impact indicators based on both the First and Second Laws of Thermodynamics. The exergy method appears to be the most suitable to achieve this purpose, as the exergy of a system is by definition the potential of this system related to the environment [2]. The relationships between the exergy and the environment concern both the consumption of natural resources and the impact of the emissions on the environment. Several attempts have been made to combine exergy and LCA to quantify the environmental impact of industrial processes, such as cumulative exergy consumption (CExC) analysis, exergetic life cycle analysis (ELCA) and so on. These works advocated the use of exergy as the metric within the LCA framework [3].

The CExC analysis has been used for many years as a useful approach for evaluation of the overall consumption of all kinds of natural resources at every step of a production process. However, the numerous attempts to obtain a direct correlation between exergy and the indicators used for estimation of the impact of the emissions on the environment are still not quite satisfying [2].

In this paper, a unified process assessment is carried out to integrate various resources and emissions associated with the life cycle of industrial processes, based on the thermodynamic concept of exergy as a common objective measure. The cumulative exergy concept is applied to analyze and optimize industrial processes for emission abatement with respect to their total environmental impact. The heat pump distillation process is studied as an interesting example.

Methodology

Exergy and Environment

From the thermodynamics point of view, exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is evaluated with respect to a reference environment, with the exergy of a system or flow being dependent on the intensive properties of the reference environment. Therefore, the reference environment must be specified completely.

The application of exergy as a measure of the impact of the emissions and wastes has been investigated [3]. It has been pointed out that the exergy content of a waste stream could be a rough measure of its potential to cause harm, despite of its incapability to measure human or eco-toxicity. The impact of waste products by means of their monetary index of harmfulness can be evaluated [2]. Another approach is that the exergy of the resources consumed by the processes of the emissions abatement is taken as a measure of environmental impact of technical systems [3].

The total exergy of a material flow is the sum of chemical, physical (mechanical and thermal), potential and kinetic components [2]. The exergy of the waste flows released to the environment account for the main fraction of the external exergy losses. In most cases the temperature and the pressure of the discharged fluids or solids are close to the environmental parameters, therefore, their physical exergy is rather small. Besides that, the potential of the emissions to damage the environment depends mainly on their chemical composition and especially, on the concentration and chemical properties of the pollutants. Therefore, the chemical exergy of pollutants as well as of the material flows, released to the environment, appears to be a more representative index, than their total exergy. However, no direct correlation was found between the chemical exergy of the pollutants and their impact on various components of the environment.

Cumulative Exergy Consumption Anaylsis

Cumulative exergy consumption (CExC) extends exergy analysis beyond a single process to consider all processes from natural resources to the final products. It is defined as the sum of the exergy contained in all resources entering the supply chain of the selected product or process. This approach can be readily extended to the life cycle by including the demand chain. This approach is related to cumulative energy consumption analysis or net energy analysis, but CExC can account for material and energy inputs along with their quality. It reflects well to what extent products and services depend on natural resources. When compared to other resource accounting methods, it has the major advantage that it is able to weigh different masses in a scientifically sound way and that it enables us to bring mass and energy onto one single scale, eliminating the fuel and feedstock discussion. In fact, different kind of resources — renewable resources (biomass, solar, wind, hydropower), fossil fuels, nuclear fuels, metal ores, minerals, water resources, and atmospheric resources — are quantified on one single scale, which is a unique feature in resource accounting.

The concept of CExC uses the method of accumulation of the primary exergy consumption to a defined point in the LCA. The analysis of CExC contributes to minimizing the consumption of natural resources and thus resulting in the smallest impact on the natural environment from the consumption of natural resources from the viewpoint of exergy. Detailed discussions of CExC analysis for many processes and systems are also given elsewhere [4]. For material in natural state, its exergy is taken as the calculated benchmark. For a specified material, energy or equipment in the process under consideration, its cumulative exergy is the sum of the benchmark exergy of the corresponding raw materials and the exergy introduced into production process. Therefore, the cumulative exergy of any product, E_C^p, in the studied system can be expressed:

$$E_C^p = \sum_i E_{C,i}^{cr} + \sum_j E_{C,j}^{or} \qquad (1)$$

where $\sum_i E_{C,i}^{cr}$ and $\sum_j E_{C,j}^{or}$ denote the cumulative exergy of construction resources and operation resources respectively.

Equivalent Cumulative Exergy Consumption

Emissions can be treated by separation and transformation so that a certain level of their environmental impact is to be achieved. A process is considered to be a sustainable process when the emission rate is below the absorptive capacity of the environment, or alternatively, below the socially acceptable levels and emission quotas based on these levels. Identifying an acceptable emission level is a complex problem, which is dependent on both environmental and social factors. Practical definitions of acceptable emission level can be based on regulatory standards and guidelines created by local, regional and national governments. In principle, a non-acceptable emission process can be adjusted to an acceptable emission process by treatment of emissions. To carry out these separation and transformation processes, which like all real processes are irreversible, CExC is for treatment of emissions also required, for short, CExCT. So the environmental impact attributable to emissions can be quantified by virtue of CExCT. Therefore, the CExC is extended to take into account environmental effects associated with emissions and not only consumption of natural resources.

The concept of equivalent cumulative exergy consumption (ECExC) is defined as the sum of CExC leading to the considered product based on an acceptable level of the environmental impact in all steps of the chain of production processes. The formula may be expressed as follows:

$$EE_C^p = \sum_i E_{C,i}^{cr} + \sum_j E_{C,j}^{or} + \sum_k E_{C,k}^d \qquad (2)$$

where EE_C^p and $\sum_k E_{C,k}^d$ represent the equivalent cumulative exergy consumption and cumulative exergy consumption for treatment of emissions, respectively.

This method uses CExC as the sole criterion to analyze a process from the standpoint of environmental protection and thus providing information of how effective a process is regarding the total consumption of natural resources based on an acceptable level of the environmental impact. The amount of natural resources required to operate a process can be quantified from the viewpoint of ECExC, and therefore, the concept of ECExC can be used as one single objective function for industrial process analysis and optimization in terms of resource use and emissions.

Case Study

For the application of the ECExC method, a separate heat pump distillation process is selected. The flowchart of the process is shown in Fig. 1 [5]. It mainly consists of two sections: the upper column and lower column. The upper column is similar to the conventional direct heat pump distillation, with feed inlet near to its bottom. From the top of the column, a part of the overhead vapour is compressed, through a mechanical compressor, to a higher pressure thus releasing its energy at a higher temperature in the upper reboiler, and the remaining part of the vapour is condensed in an auxiliary condenser. A part of the mixed condensate is withdrawn as the distillate, and the remainder is returned as the reflux to the upper column. The lower column works as a stripper. The feed to the lower column is the liquid stream from the upper reboiler, and the outcoming vapour from the column goes into the bottom of the upper column.

The operation conditions are taken as follows: Feed mixture consists of ethanol and water. The atmospheric saturated feed at a flow rate of 7.2 ton/h containing 0.64 v/v ethanol is considered. The feed is distilled to give top product of composition at least 0.95 v/v ethanol, and bottom product of composition at most 0.001 v/v ethanol.

There exits two main operating resources electricity and steam in this process. From the viewpoints of economics, there exists trade-offs among the operating resources using the inlet vapour flow rate to compressor as an optimization variable [5]. The similar trade-offs exist for this process in terms of ECExC, i.e., the objective function of optimal design is the minimization of annual ECExC of operating resources. Therefore, the optimal mathematical models of this process can be expressed as:

$$EE_C^p = EE_C^e + EE_C^s \qquad (3)$$

where EE_C^e and EE_C^s denote the equivalent cumulative exergy consumption of electricity and steam respectively.

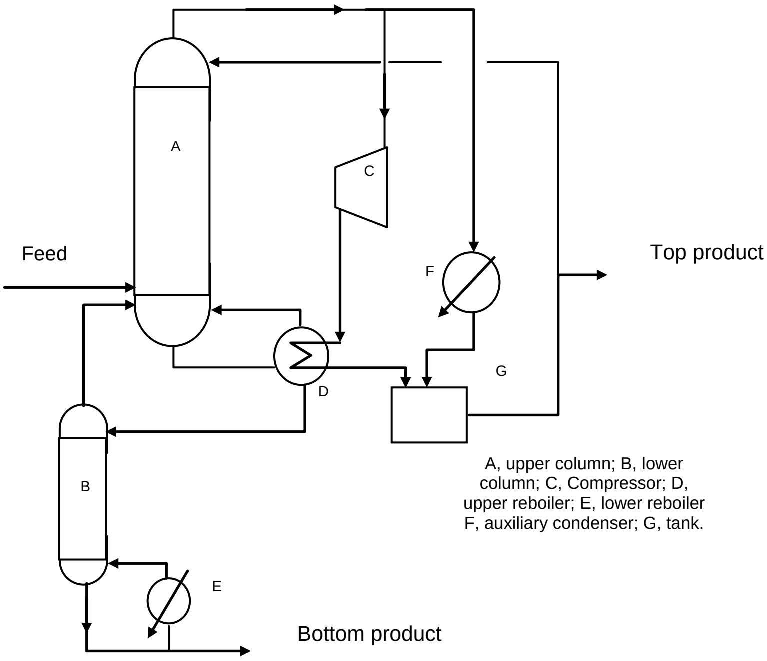

Fig. 1 Flowchart of separate heat pump distillation

Environment Impact Analysis of Emissions

In the present context, the operating resources mainly include electricity and steam. This is equivalent to extending the system boundaries to include the production of the electricity and steam from natural resources. There are many kinds of emissions in the production of electricity and steam. In principle, the proposed framework allows to include all types of emissions. Particular attention is taken for CO_2 emission in this case study, for it contributes to the greenhouse effect, and it is emitted in large quantities by the industrial processes [6], and the quantitative correlation between steam (or electricity) and CO_2 is also available. Therefore, for the sake of simplicity, the requirement for CExCT is limited to the treatment of CO_2 in this paper.

Data Sources

It is shown that the CExC of electricity is 2.86 MJ/MJel [6], and the CExC of steam is 3.86MJ/kg steam [7]. The CExCT of CO_2 is 5.86MJ/kg CO_2 for the case of separation of 90% CO_2 out of the flue gases, compression and storage in empty gas fields [8]. For the generation of electricity based on gas combustion, 0.053kg CO_2 is produced for 1MJ CExC of electricity, resulting in 0.31 MJ CExCT /MJ CExC electricity. This results in an ECExC of 3.75MJ/MJel for electricity supply. For the calculation of CExCT of steam production, the use of gas (97.5m^3/ton steam), oil (7.3kg/ton steam), electricity (10.1 MJel) and water (1000kg/ton steam) have to be taken into account. Since 1kg oil delivers 3.08 kg CO_2, it is found that the CExCT of oil is 18.05MJ/kg. With these above data, a CExCT of steam is 1.06MJ/kg steam [8], and thus an ECExC of steam is 4.92 MJ/kg steam. The results on the CExC, CExCT and ECExC are summarized in Table 1. The economic costs of operating resources are taken as follows: unit price of electricity is 0.41Yuan/(kW·h) and the cost of saturated steam is 20Yuan/ton [5].

Table 1. CExC and ECExC of different operating resources (in MJ)

Items	CExC	CExCT	ECExC
CO_2 (kg)		5.86	
Electricity (MJ)	2.86	0.89	3.75
Steam (kg)	3.86	1.06	4.92

Results and Discussion

Aspen plus process simulator is used for rigorous modeling of this process with the following postulation: UNIQUAC thermodynamic model is used for evaluation vapour-liquid phase equilibrium and enthalpy; Molar reflux ratio is 2.8 for this process; Maximum flooding is 80%; Isentropic efficiency of compressor is 0.72; Column pressure is 101.33 kPa; Pressure drops in the columns and heat exchangers are nil; Annual operation time is 7200h. Besides, bubble cap trays are considered for the columns, and single stage isentropic compressor is considered for vapour compression. The minimum approach temperature in the upper reboiler is taken as 10℃, and in the auxiliary condenser as 40℃. The mathematical models are solved by the Broyden method, using simultaneously the sequential quadratic programming (SQP) optimization procedure. The optimal simulated results over one year operation are shown in Table 2.

Table 2. Optimal results of various objective functions

Items	ECExC	Economics
Inlet vapour flow rate (ton/h)	16.32	14.79
Minimum objective value	6.07×10^{7} MJ	1.08×10^{6} Yuan

From the results listed in Table 2, it can be seen that the optimal value of the inlet vapor flow rate to compressor from the minimization of annual ECExC is bigger than the one from economics. The results imply that the optimal design of using the proposed method consume more electricity and thus less steam than that of economics. However, such results can satisfy the needs of the environmental impact minimization of industrial processes from the ECExC method, and furthermore are stable compared with the ones from economics [7].

Conclusions

Based on the exergy as a common objective measure for various forms of resources and emissions, a unified environmental process assessment is employed in the paper to assess heat pump distillation process within a specified life cycle in terms of resources use and waste emissions. The combination of exergy accounting and process assessment makes it possible to fully integrate the resources and environment impacts in a common unit, thus provides a better frame to evaluate the overall systems performance. The illustrative example discussed herein provides an idea of the capabilities of the method and demonstrates that ECExC provides a novel and different insight in design optimization tasks.

References

[1] D. Maes, S.V. Passel, Environ. Impact Asses. 45 (2014) 19-29.

[2] S. Y. Yang, S.Y. Yang, Y. Qian, J. Clean. Prod. 108 (2015) 1019–1027.

[3] L. Stougie, H. J. van der Kooi, Energy convers. Manage. 107 (2016) 60-66.

[4] A Valero, J. Uche, A. Valero and A. Martinez, Energy 34 (2009) 2101–2107.

[5] P. Zhu, X. Feng, Can. J. Chem. Eng. 81 (2003) 963–967.

[6] W. Stanek, L. Czarnowska, K. Pikoń, M. Bogacka, Energy 92(2015) 341-348.

[7] D. Laner, H. Rechberger, W. de Soete, S. de Meester, Waste Manage. 46 (2015), 653-667.

[8] Dewulf, H. V. Langenhove, J. Dirckx, Sci. Total. Environ. 273 (2001) 41–52.