EXERGY ANALYSIS AND EXERGO-ECONOMIC OPTIMIZATION OF INDUSTRIAL PROCESSES

P. LE GOFF and J.-M. HORNUT

Laboratoire des sciences du génie chimique[1]

OPTIMISATION DES PROCÉDÉS INDUSTRIELS PAR ANALYSE EXERGÉTIQUE ET EXERGO-ÉCONOMIQUE

L'évaluation globale d'un procédé peut être faite soit au moyen d'un bilan exergétique, soit par l'intermédiaire d'un bilan économique. Dans tous les cas, un procédé peut être optimisé en déterminant le meilleur compromis entre les différents flux mis en jeu.

EXERGY ANALYSIS AND EXERGO-ECONOMIC OPTIMIZATION OF INDUSTRIAL PROCESSES

The overall evaluation of a process can be made by exergy accounting or by financial accounting. In all cases, a process can be optimized by determining the best compromise between the various input fluxes.

OPTIMIZACIÓN DE LOS PROCEDIMIENTOS INDUSTRIALES POR ANÁLISIS ENERGÉTICO Y EXERGOECONÓMICO

La evaluación global de un procedimiento se puede llevar a cabo por medio de un balance energético, o bien, mediante un balance económico. En cualquier caso, se puede optimizar un procedimiento determinado para conseguir el mejor compromiso entre los distintos flujos que entran en juego.

---

(1) CNRS – ENSIC – INPL
Nancy - France

INTRODUCTION

Industrial processes can be represented as open systems where available energy (≡ exergy) enters, utilized energy (≡ exergy content of goods and services) exits, and some degraded energy (≡ destroyed exergy) is rejected into the environment.

The overall evaluation of a process can be made by **energy** accounting (in terms of exergy or of primary fossil energy) or by **financial** accounting (in terms of national or foreign currency). In all cases, a process can be optimized by determining the best compromise between the "values" of the various input fluxes.

1 OBJECTIVES OF THE RESEARCH PROGRAMMES

The first objective is to determine a general **optimization criterion** for minimizing the irreversibilities in the elementary unit processes such as heat, mass and momentum transfer, chemical reactions, dispersion and coalescence of phases, etc.

The second objective is to apply the criterion to a number of industrial unit operations: heat exchangers, distillation columns, gas-liquid absorbers and desorbers, dryers, chemical reactors with thermal effects, each operating at steady or unsteady state.

The third objective is to apply the criterion to global industrial processes, operating at steady state and to compare, in each case, the entropic (or exergetic) optimum with the economic optimums (operating costs and/or investment costs).

2 THE THEOREM OF "EQUIPARTITIONED" IRREVERSIBILITIES

D. Tondeur and E. Kvaalen published in 1987 [1] a paper entitled: “Equipartition of entropy production. An optimality criterion for transfer and separation processes”. The first five lines of the abstract of their paper present the theorem: “In a contacting or separation device involving a given transfer area and achieving a specified transfer duty, the total entropy produced is minimal when the local rate of entropy production is uniformly distributed (equipartitioned) along the space and/or time variables. This property is demonstrated under the conditions of classical nonequilibrium thermodynamics: linear flux-force relations and Onsager's reciprocity relations.”

In the last five years, we have applied this theorem to a number of unit operations in chemical engineering, and we have checked its validity under conditions where linear non-equilibrium thermodynamics are applicable.

Because industrial processes are generally nonlinear, it is of considerable practical importance to extend the theorem to the much larger domain of nonlinear relationships between fluxes and forces. This important challenge will be addressed in this work.

3 A SIMPLE APPLICATION EXAMPLE: A STEADY STATE HEAT EXCHANGER

In a conventional heat exchanger, entropy is created (or exergy destroyed) in four elementary processes: heat transfer from the hot fluid to the wall, heat transfer from the wall to the cold fluid, momentum transfer (loss of mechanical energy) by friction in both fluids.

Let us first consider a differential element of the hot half exchanger.

We define the Specific consumption of Overall Exergy, *SOE*, by the following ratio:

$$SOE = \frac{\text{(exergy consumed)}}{\text{(exergy crossing the wall)}}$$

$$= \frac{To\ \text{(entropy generated)}}{To\ \text{(entropy crossing the wall)}}$$

The *SOE* results from the addition of two terms:

$$SOE = STE + SME$$

Where *STE* is the “Specific consumption of Thermal Exergy” and *SME* is the “Specific consumption of Mechanical Exergy”. The following expression of *STE* and *SME* have been previously established [2]:

$$STE = K_3 \cdot d_h \cdot q \cdot Re^{n-1}$$

$$SME = K_4 \cdot d_h^{-3} \cdot q^{-1} \cdot Re^{3-m}$$

Where $q = \Delta Q/\Delta A$ is the density of heat flux ΔQ through the surface area ΔA of the wall.

Where n and m are the exponents in the following expressions of the Stanton number, and of the friction factor:

$$St = K_1 \cdot Re^{-n}$$

$$f/2 = K_2 \cdot Re^{-m}$$

and the K_i are proportionaly constants for each fluid.

With the general objective of minimizing the *SOE*, let us consider the three following particular cases:

1rst case: the hydraulic diameter d_h and the Reynolds Number are fixed. The heat flux q is varied, for example by varying the temperature T_p of the wall by acting on the cold fluid.

2nd case: d_h and q are fixed. The fluid flow rate and therefore the Reynolds number is varied.

3rd case: q and *Re* are fixed. The hydraulic diameter is varied.

In the first case, the expression of *SOE* becomes:

$$SOE = X_1 \cdot q + Y_1 \cdot q^{-1}$$

The optimum value of q is calculated as:

$$q_{opt} = \sqrt{\frac{Y_1}{X_1}}$$

and the corresponding minimum value of the *SOE* is such that:

$$STE_{min} = SME_{min} = \frac{SOE_{min}}{2} = \sqrt{X_1 Y_1}$$

We state: “At the optimum heat flux, the exergy consumed in the heat transfer is equal to the exergy consumed in the mechanical friction”.

In the second case, the expression of the *SOE* becomes:

$$SOE = X_2 \cdot Re^{n-1} + Y_2\ Re^{3-m}$$

At the optimum value of *Re*, which minimizes *SOE*, the two components of the *SOE* are calculated to be in the inverse ratio of their exponents, that is:

$$\left\langle \frac{STE}{SME} \right\rangle_{opt} = \frac{3 - m}{1 - n}$$

It is remembered, that, for example, in the turbulent regime, the exponents are:

$$n = m \ \# \ 0.2$$

Therefore:

$$\left\langle \frac{STE}{SME} \right\rangle_{opt} = 3$$

In the third case, we have similarly:

$$SOE = X_3 \cdot d_h + Y_3 \cdot d_h^{-3}$$

Whence at the optimum:

$$\left\langle \frac{STE}{SME} \right\rangle_{opt} = 3$$

Generalisation:

It can be observed that in each case, the ratio (*STE/SME*)opt is constant, in the order of 1 to 3 in turbulent regime.

This result is, in fact, a particular case of a general theorem of the “geometric programming” [3] saying that this ratio only depends upon the exponents of each term.

Furthermore, we obtains:

$$\left\langle \frac{STE}{SME} \right\rangle_{opt} = \left(\frac{T_f}{T_p} - 1 \right) \left(\frac{Q}{W} \right)_{opt}$$

Where W is the flux of mechanical energy degraded by friction.

As an example, we consider a heat exchanger with a wall temperature T_p = 500 K and a fluid bulk temperature T_f = 520 K. We obtain:

$$\left(\frac{Q}{W} \right)_{opt} = 25 \text{ to } 75$$

As a general conclusion, the ratio *Q/W* is always much greater than one, at the minimum of exergy consumption.

3.1 Balance of economic value

Let us call V_t the value of one joule of thermal exergy, and V_m that of a joule of mechanical exergy.

The specific cost of overall consumed exergy is:

$$SCOE = V_t\, STE + V_m \cdot SME$$

The previous reasoning is still valid but it is now applied to the partial costs of the two components.

The ratio $\left(\frac{V_t \cdot STE}{V_m\ SME} \right)_{opt}$ is equal to 1 in the first case, equal to 3 in the third case and equal to $\frac{3 - m}{1 - n}$ in the second case.

For example in the first case, the cost of the thermal exergy consumed is equal to the cost of mechanical exergy consumed.

The optimum value of the heat flux which minimize the overall operating cost is:

$$q_{(opt\ cost)} = \sqrt{\frac{V_1 Y_1}{V_m X_1}} = \frac{V_1}{V_m} \cdot q_{opt\ exergy}$$

4 FURTHER EXTENSIONS TO BE CONSIDERED

- In gas-liquid contacting columns used in operations such as distillation, absorption or desorption, six elementary transfer processes destroying exergy must be taken into account. It is known that the exergy efficiency of these processes is small (≈ 10%) at least in the present conventional technology.
- An increasing number of industrial separation processes are operating in a batch mode. This is especially the case for permeation processes (such as chromatographic columns), in which several heat and mass transfer processes occur within the porous solid, each destroying exergy. All of these processes must be considered in the overall optimization.
- Industrial operations use a great number of materials made of dispersed phases (small solid particles, gas bubbles, liquid drops, etc.) with a large surface area per unit volume. It is known that the exergy efficiency of the dispersion processes used for creating such large surfaces is very small (≈ 1%).
- In each case, an economic “value” must be ascribed to each unit of exergy to determine the conditions which minimise the overall cost. In the simplest case, when the value of each type of exergy is a constant, the theorem of equipartition of component is still valid, but with respect to partial costs: for example, in the case of the heat exchanger, the theorem states that, at the optimum, the cost of the thermal exergy consumed is equal to the cost of the mechanical exergy consumed.

Such a simple conclusion is replaced by a more complex relationship in the general case of a non-proportionality between cost and exergy, especially when equipment costs (which involve non-linear scale factors) are included.

REFERENCES

1 Tondeur D. and Kvaalen E. (1987) Equipartition of entropy production. An optimality criterion for tranfer and separation processes. *Industrial & Engineering Chemistry Research,* 26, 50.

2 de Oliveira S. Jr, Schwarzer B., Le Goff P. and Tondeur D. (1991) Exergy destruction minimization and cost optimization of heat and mass transfer exchangers, through the equipartition of irreversibilities. *International Conference on the "Analysis of Thermal and Energy Systems"*, Athens, June 3-6, 1991.

3 Beightler C. and Phillips D.T. (1976) *Applied Geometric Programming,* John Wiley.

Final manuscript received in December 1997