An Exergy Analysis Contribution to Energy Optimization of Industrial Processes

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Conventional Exergy Analysis

• Evaluates the magnitude of exergy losses (losses in thermodynamic potential to produce work) in every unit operation
Conventional Exergy Analysis (cont ’d)

• One of the typical exergy analysis guideline is « Tackle the biggest loss first ». Sometimes this does not work.
• It is not clear how data from conventional Exergy Analysis should be used to improve a given design.
• Nevertheless indicates the major causes of thermodynamic imperfection for any process (not only thermal ones).
• To minimize the overall irreversibility an optimization procedure based on numerical solution of complex mathematical models is required.
An Optimization Approach

• **Structural Optimization.** Synthesis of alternative structures which includes selection of processing steps and connections between steps.

• **Parameter Optimization.** Changing the operating conditions within a fixed structure.
A Superstructure Approach for Structural and Parameter Optimization.

• A structure of an industrial process known as a superstructure is first created. It embeds within it all feasible process operations and all feasible interconnections that are candidates for an optimal design.

• The design problem is next formulated as a mathematical problem by using two type of variables: continuos and integer ones.

• Once the problem is formulated mathematically, its solution is carried out through implementation of an optimization algorithm. Economic potential is maximised or cost is minimised in a structural and parameter optimization.
Difficulties Related with Optimization of Industrial Processes.

In certain class of problems:

• The research space is too large;
• The initial values are sometimes badly defined or not defined at all;
• The lower and upper bounds are sometimes unknown;
• In many cases the resulting profile of an objective function is strongly nonlinear, nonconvex and includes numerous discontinuities;
• The presence of many local optima;
• Often a design engineer has difficulties dealing with large process models for optimization due to the lack of understanding. As a result he is removed from the final decision-making process.
The Role of Thermodynamics

Thermodynamics itself can not replace the detailed simulation and optimization procedures, but it allows:

- Simplify mathematical models used for optimization.
- Identify the lower and upper bounds for energy efficiency.
- Formulate a «good » initial guess (the starting point) for an optimization procedure.
- Reduce the solution space of a problem making the optimization simpler.
How to Combine Exergy Analysis and Mathematical Optimization Technique?

• The development of suitable thermodynamic concepts (based on the second law) to formulate the problem and simplify the search procedure to achieve global optimization. In this presentation a new interpretation of exergy balance around a process is represented by a simple diagram, thermodynamic intensity vs. flows of thermodynamic extensities. The concepts are discussed in the context of three types of thermodynamic processes, reversible, endoreversible and irreversible.
Conceptual Design of Thermochemical Refrigerators Solid-Gas.


- Two major problems of the design are the right choice of materials and structures of the processes.

- The main objective is to develop new refrigeration cycles with improved COP values.
Single Effect Solid-Gas Thermochemical Refrigerator (TR)

\[ \text{COP} = \frac{Q_E}{Q_D} \]

Design problem:
- \text{max COP}
- \text{min } T_S
A Reversible Approach Based on Exergy

• Systematic generation of the design alternatives for the ideal processes with predetermined targets (maximum COP and minimum Ts values).
• In the next design step the corresponding real processes having the same structure as the selected ideal ones have to be identified and experimentally validated.
Energy Paths within a Single Effect TR
Correspondence between Clausius-Claperon and Exergy Based Diagrams for Single Effect TR

\[ Q_C = \Delta H_c \]

\[ Q_D = \Delta H_r \]

\[ Q_E = \Delta H_{ev} \]

\[ Q_S = \Delta H_r \]

\[ T_E \]

\[ T_C = T_O \]

\[ T_S \]

\[ T_D \]

\[ -1/T \]

\[ p_{\ell} \]

\[ p_h \]

\[ \ell_{np} \]

\[ Q_{D-S} \]

\[ Q_E \]

\[ Q_S \]

\[ Q_D \]

\[ Q_{D-C} \]

\[ Q_d \]

\[ Q_d, s \]

\[ Q_{d,c} \]

\[ \theta_{D} \]

\[ \theta_{S} \]

\[ \theta_{E} \]

\[ \theta_{D} \]

\[ \theta_{C} \]

\[ \theta_{S} \]

\[ \theta_{E} \]

\[ \theta_{D} = \theta_{T} \]

\[ \theta_{C} = \theta_{T} \]

\[ \theta_{S} \]

\[ \theta_{E} \]

\[ Q_{C} = D H_c \]

\[ Q_{D} = D H_r \]

\[ L/G \]

\[ S/G \]

\[ Q_{E} = D H_{ev} \]

\[ Q_{S} = D H_r \]

\[ Q_{E} = D H_{ev} \]

\[ Q_{D} = D H_r \]

\[ L/G \]

\[ S/G \]

\[ Q_{S} = D H_r \]

\[ Q_{E} = D H_{ev} \]

\[ Q_{D} = D H_r \]

\[ -1/T \]

\[ \ln p \]

\[ Q_C = D H_c \]

\[ Q_D = D H_r \]

\[ L/G \]

\[ S/G \]

\[ Q_S = D H_r \]

\[ Q_E = D H_{ev} \]

\[ ph \]

Area (1-3-4-5-6-7) = Area (9-8-7-10)
Add a new energy path.

\[ \text{COP}_i = \lambda_{E-C} + \lambda_{E-C} \]
Discard the areas corresponding to transit exergy and exergy of the produced heat.

$L’option de la conception N 1.$
Technical Feasibility of a Double Effect (DE) Thermochemical System (two evaporation units)

The COP value of the DE system is 1.8 times higher than the SE system.
The Thermodynamic Criteria to Manage Food Deep Chilling Tray Tunnel Operation


OBJECTIVE

What are the parameters of the process which allow to intensify the production given the finite size of the process?
Endoreversible Approach Based on Exergy.

• A complex system may be presented by combination of ideal processes and resistances where the latter are the sources of exergy losses.
• Capital cost may be taken into account indirectly by imposing the constraints on equipment.
• Simplified but practical models for optimization can be proposed.
HYPOTHESES

● Overall heat transfer coefficients

● The fan power does not contribute to the refrigeration load.

● Compressor Model (isentropic efficiency)

● Heat transfer from the slab edges is ignored.

● The food output temperature varies inside a specified interval
Exergy Balance

\[ E_C = P + D \]
\[ \Delta E = \Delta H - T_0 \Delta S \]
\[ \Delta E = -Q_E - T_0 \int_{T_0}^{T_{out}} \frac{dQ}{T} \]

Equivalent temperature potential \( \tilde{\theta} \)

Exergy variation

\[ \Delta E = -Q_E \tilde{\theta} \]
Graphical Representation of the Exergy Transfer

\[ W = P + D \]

\[ P = -Q_E \tilde{\theta} \]

Carnot Refrigerator

\[ Q_E (\theta_C - \theta_E) = W (1 - \theta_C) \]

Exergy Losses

\[ D = Q_E (\tilde{\theta} - \theta_E) + (Q_E + W) \theta_C \]

\[ Q_E = f_{\downarrow} (-\tilde{\theta}) \]
Two Criteria of Performance

\[ P \] : Exergy power

\[ d = \frac{D}{m} \] : Destruction of specific exergy
Exergy Power and Destruction of Specific Exergy as a Function of Relative Food Mass Flow Rate

Is it better to have a high mass production at high food temperatures, or rather reduce the mass production but reaching lower output food temperatures?
A Thermodynamic Approach to Conceptual Design of Hybrid Separation Processes.


- Industrial separation processes are amongst the most capital and energy intensive processes.
  - Although energy inefficient (≈ 10% thermodynamic efficiency), distillation accounts for about 15% of the energy consumed by the Canadian manufacturing sector.
  - There is a very large and old (30-40 years) capital stock of distillation columns in the petroleum, petrochemical and chemical industries.

- As a result there is an important potential to improve the energy efficiency and/or productivity of these sectors by revisiting the design and hybridizing these installations with new separation technologies.
• One possible approach to improve the separation process efficiency is to combine the distillation column with an auxiliary more efficient separator, for example a membrane.
Hybrid Process Configurations

Parallel Hybrid Structure for Close Boiling Separation
Challenge

Given that a column separating zeotropic binary mixtures involves many trays, there exists a large number of possible parallel hybrid architectures.
A column with 140 trays generates more than $5 \times 10^7$ possible parallel design arrangements with a single membrane unit.

Furthermore, the following parameters are unknown:

- The membrane size (i.e. surface area)
- The column’s feed position
- The operating conditions of the hybrid.

Only the characteristics of the column’s input and product streams are known.

- The combinatorial nature of the problem and the non-convexities present in the model equations often give rise to different results when it is formulated as a mathematical programming problem and solved with various initial guesses of the hybrid’s architecture and operating conditions.
Proposed Approach

- Using engineering insights, thermodynamics and mathematics to provide an efficient, accurate and reliable method to determine minimal energy requirements for distillation when coupling with a membrane unit.
This approach consists in introducing a new performance metric, termed *Power of Separation*, which:

- takes into account both process productivity and process selectivity;
- is useful for the design/retrofit of single units and process networks;
- is linked with the exergy consumption and the size of equipment.
Power as a Characteristic of Separation Process Yield

- The yield of any type of engine is characterized by power.

- What about separation processes?
  - Power is consumed, not produced as in the case of engines.
  - The process outputs are mass flows, not energy flows.

- Exergy, which is a measure of both mass flow rate and its quality (species concentration, pressure and temperature) may be useful to characterize a separation process’ yield.
Compositional Exergy

Consider a steady-state continuous separation process.

\[ \text{Ex} = RT_0 \left[ \sum_{i,k} \text{Out}_k z_{i,k}^{\text{Out}} \ln \left( \gamma_{i,k}^{\text{Out}} z_{i,k}^{\text{Out}} \right) - \sum_{i,j} \text{In}_j z_{i,j}^{\text{In}} \ln \left( \gamma_{i,j}^{\text{In}} z_{i,j}^{\text{In}} \right) \right] \]
The enrichment (in terms of concentration) is the same for both cases, but the variation of compositional exergy is different.
The power of separation of the process ($P_{sep}$) is defined as

$$P_{sep} = RT_0 \left[ \sum_{i,k} Out_k z_{i,k}^{Out} \ln \left( z_{i,k}^{Out} \right) - \sum_{i,j} In_j z_{i,j}^{In} \ln \left( z_{i,j}^{In} \right) \right]$$

and

$$Ex = P_{sep} + RT_0 \left[ \sum_{i,k} Out_k z_{i,k}^{Out} \ln \left( \gamma_{i,k}^{Out} \right) - \sum_{i,j} In_j z_{i,j}^{In} \ln \left( \gamma_{i,j}^{In} \right) \right]$$

Excess change in Gibbs free energy between output and input streams of the process.
Additivity of Power of Separation

\[
\left( P_{sep} \right)_A = \left( P_{sep} \right)_B + \left( P_{sep} \right)_C
\]
Hypothesis to be validated.

For a given number of distillation trays, the minimum energy requirement of a distillation column is achieved if the column’s power of separation is minimized, which means that the membrane’s power of separation is maximized.
Example: Retrofit of a C3-Splitter

Math. Prog. Approach (GAMS-CONOPT)

- \( r = 12.6790 \)
- \( x_D = 0.99 \)
- \( 137 \)

- \( S = 21.3927 \text{ m}^2 \)
- \( M = 2 \text{ mol/s} \)
- \( y_M = 0.4439 \)
- \( x_F = 0.44 \)
- \( .62 \)
- \( .92 \)
- \( .61 \)
- \( .31 \)

- \( F = 2.87 \text{ mol/s} \)

New Approach

- \( r = 12.9822 \)
- \( x_D = 0.99 \)
- \( 137 \)

- \( S = 17.4955 \text{ m}^2 \)
- \( M = 2 \text{ mol/s} \)
- \( y_M = 0.44 \)
- \( x_F = 0.44 \)
- \( .63 \)
- \( .96 \)
- \( .34 \)

- \( F = 2.87 \text{ mol/s} \)

(a) (b)
## Methodology Efficiency

<table>
<thead>
<tr>
<th>New approach</th>
<th>Ten trials of traditional approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Equations</td>
<td>5</td>
</tr>
<tr>
<td>Number of Variables</td>
<td>8</td>
</tr>
<tr>
<td>Number of solver iterations</td>
<td>46 (\approx) (575 \times 10 = 5750)</td>
</tr>
</tbody>
</table>

- The new method requires 125 times less iterations than the traditional method.
Practical Application

- The approach was applied to an existing plant for ethane/ethylene separation (C2 splitter).

- Energy savings compared to the base case is 21 % which presents the reduction of 3.7 MW of electrical power.