DESIGN OPTIMIZATION OF POWER AND COGENERATION SYSTEMS

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Keywords: Energy-intensive systems, Performance/cost analysis, Optimal design, Second-law-based decomposition, Cogeneration, Constant and variable demands

Contents

Summary

The article focuses on aspects of predicting the performance and the cost of fossil-fueled energy-intensive systems while still in their design phase. A second law-based optimization methodology is presented for achieving, by design, higher efficiency and lower product costs for power and cogeneration systems. The methodology is one of the tools of “thermoeconomics.” First the base-load design case is considered. Five gas turbine system concepts are analyzed and the results are summarized on a cost-efficiency diagram. The prediction of off-design performance as a function of power load ratio is then considered using a simple combined cycle as an example. The case of variable load design is then considered. A gas turbine power-heat cogeneration system is assumed to power, cool and heat a small community as a grid-independent system. A screening method is established to examine a larger number of configurations for minimum fuel penalty arising from off-design performance and demand-production mismatches. Finally a simple method is presented for the optimal operating mix of a facility of power plants.

1. Introduction

Sustainable development, driven by increasing world population and rising standard of living, depleting fuel resources and deteriorating environment, forced new directions of research and development and shaped the thoughts and attitude of societies. Until new fossil fuel-independent breakthroughs in power generation are achieved, scientists and engineers have to face the challenge of achieving higher efficiency and lower emissions at lower cost. This challenge imposes intensive analysis of systems in their design phase to evaluate the cost-effectiveness of a design modification or a new design concept by predicting its cost-efficiency-emission characteristics. This article deals with a tool for the needed intensive analysis of energy systems in general with special focus on power generation and cogeneration systems. The tool uses the modular approach to system modeling and is known as “thermoeconomics.” First the case of base-load systems is considered for optimal design. In this case fueling and production are time-independent. The case of variable-load design is then considered in which production and/or fueling are time-dependent. The off-design performance of a system design, given a control strategy, is then derived. Because of the complexity of the derivation, a screening method for variable-load systems is then presented. The screening limits the complexity of the derivation to the most competing systems. Application examples are presented. The bibliography guides to details related to the article as well as to further reading. The computer programs handling the examples are available free of charge upon request.

2. The Optimal System Design for Time-independent Production

The interacting resources of an energy-conversion device are first considered followed by their quantification. The interactions among devices making up a production system are then considered. Based on these considerations, a decomposition strategy for the optimization of a system of a given configuration for a cost objective function is established. The modular approach to modeling enhances the handling of different configurations. An efficient search tool for the optimal designs for energy-intensive systems in general is thus established. The search tool is then applied to base-load power production.

2.1 The Interacting Resources of an Energy-conversion Device

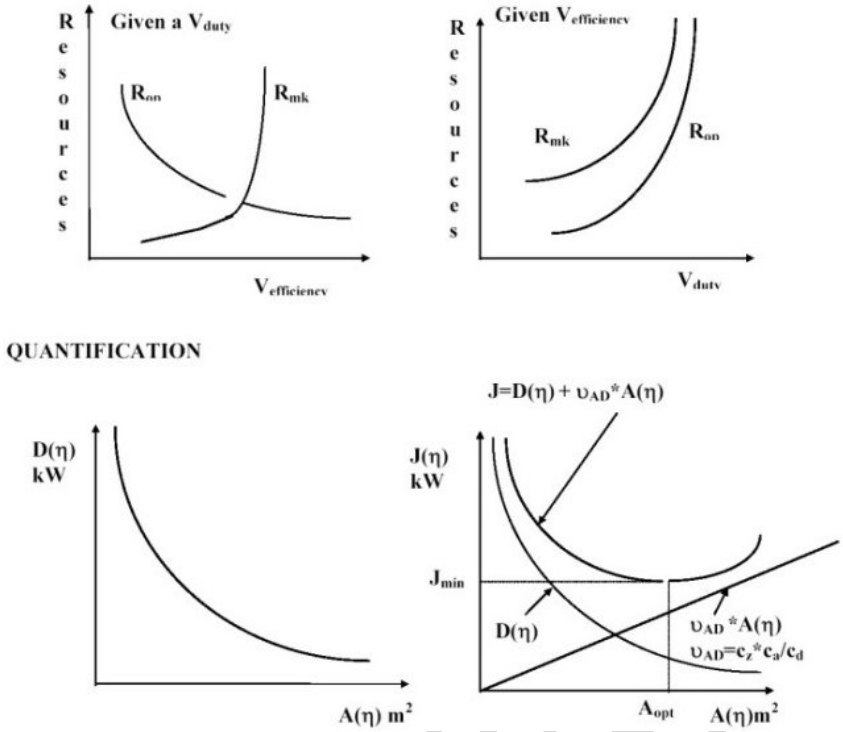

Figure 1. Making and operating resources of an energy conversion device.

Any energy-conversion device requires two resources: Resources to make it R_{mk} and resources to operate it R_{op}. These two resources increase with the device duty and are in conflict with the device performing efficiency. Since both resources are expenses, their minimum sum is sought. Figure 1 illustrates these two interactions and their sum qualitatively.

2.1.1 Quantification of the Making and Operating Resources

The Making Resources: The leading resources of the making resources involve materials, R&D, design and manufacture. The capital cost of a device $\underline{Z}$ in monetary units best reflects these leading resources. This in turn may be expressed by characterizing dimensions and unit costs:

$$\underline{Z} = \sum c_{ai} * A_i \, . \qquad (1)$$

Usually one characterizing surface and its unit cost is adequate quantification of Z and hence the rate of the making resources becomes:

$$R_{mk} = Z = c_z * c_a * A \qquad (2)$$

where Z a capital cost rate and c_z is a capital recovery rate.

The operating resources: the leading resources of the operating resources are the fueling resource and other materials and maintenance resources. The fueling resource is what the device pulls from an input fueling resource intended to produce a sought product. Ideal devices convert without pulling from the input resource. In thermodynamic terms, the pulling is simply the lost work induced by the device, often called exergy destruction. The relations between energy, entropy, work, exergy and exergy destruction are explained and formulated in detail under what is known as second law analysis. See bibliography for guidance. All devices destroy exergy for their operation depending on their performing efficiency. Only ideal devices (100% efficiency), which do not exist, have zero exergy destruction. The rate of operating resources can be quantified in monetary units as follows:

$$R_{op} = c_d * D \qquad (3)$$

where D is the rate of exergy destruction of a device depending on its performing efficiency and c_d is the price of the exergy destruction depending on the position of the device in a system among other devices and on the price of the fuel feeding a system. The objective J_i of a device i at the device level in monetary units is:

$$\text{Minimize } J_i = R_{mk} + R_{op} = c_{zi} * c_{ai} * A_i + c_{di} * D_i \qquad (4)$$

where both A and D are functions increasing with duty and at conflict with performing efficiency.

Equation (4) expresses cost as a cost of an exergy destructor and its destruction. Equation (4) in relative units, say kW, is:

$$\text{Minimize } J_i = D_i + \upsilon_{AD} * A \qquad (4a)$$

where the relative value of matter to energy is $\upsilon_{AD} = c_{zi} * c_{ai} / c_{di}$.

2.2 Making and Operating Resources of a System of Devices

A production system consists of energy conversion devices that had their different making resources but usually share one fueling resource to produce a product or products. The objective function at a system level given a sizing parameter for the products (e.g. one product rate as the independent product) is

$$\text{Minimize } J_s = c_f * F + \sum c_{zi} * \underline{Z}_i = c_f * F + \sum c_{zi} * c_{ai} * A_i \qquad (5)$$

where the capital cost $\underline{Z}_i$ of each device is represented by one characterizing dimension A_i. Express Eq. (5) in terms of making and operating resources:

$$J_s = {}_{i=1}\Sigma^n \left(c_{di} * D_i + c_{zi} * c_{ai} * A_i \right) = {}_{i=1}\Sigma^n J_i \qquad (6)$$

where n is the number of devices.

If the system can be decomposed into pairs of destructors and destructions, a system can be optimized piece-wise. That is to say

$$J_{s\,\min} = {}_{i=1}\Sigma^{n} J_{i\,\min} \tag{7}$$

Piece-wise search for optimality greatly enhances the search and gives insight into improvement. A decomposition strategy is now sought having in mind this kind of piece-wise optimization of Eq. (7).

2.3 A Decomposition Strategy

The objective function, Eq. (5), is multidisciplinary. At least four disciplines are participating: Thermodynamics for F, Design for $\{A_i\}$, Manufacture for $\{c_{ai}\}$ and Economics for c_f and $\{c_{zi}\}$. Two-level decomposition strategy is thus needed: at the discipline level as well as at the device level.

2.3.1 Decomposition at the Discipline Level

Let the discipline of Thermodynamics be the active discipline since a system is born in this discipline and is the only discipline that sees all parts of the system. Get needed information from other disciplines in terms of the variables of the thermodynamic discipline $\{V_{TH}\}$ such as pressure, temperatures, power, mass rate, heat rates and efficiency parameters. This simply decomposes the system at the discipline level. One rational basis of achieving this is *the concept of costing equations*. The concept translates the desired information from other disciplines into the thermodynamic language by manipulating design models by designers, manufacture models by manufacturers, and economic models by economists. The translation eventually leads to the following ingredients of costing equations:

$$\text{Characterizing dimension A} = \text{minimized A}\,(\{V_{\text{duty}}\}, \{V_{\text{efficiency}}\}) \tag{8}$$

$$\text{Unit cost } c_a = \text{minimized ca}\left(\text{press, temp, A}_{\text{material}}\right) \tag{9}$$

$$\text{Fuel } c_f \text{ and capital } \{c_z\} = \text{discrete, time-and-location dependent} \tag{10}$$

With this pre-prepared translation all analysis and optimization can be performed within the thermodynamic domain. Design and manufacture details are retrievable from the models used. Market-place costs of devices do exist in terms of a duty variable such as \$/kW and \$/(kg/h) but are not explicit in efficiency variables which are needed for balancing making and operating costs. A number of design models have been described by the author along with a list of translated costing equations and an example of their derivation. No claim is made regarding the generality of the presented costing equations. The only claim is the rationality of costing for design improvement.

2.3.2 Decomposition at the Device Level

Decomposition at the device level simply introduces the principle: "*optimal devices lead to their optimal system*."

Express the exergy destruction D of a device in the same way as its characteristic dimension A i.e. $D = D\left(\left\{\mathrm{V_{duty}}\right\},\left\{\mathrm{V_{efficiency}}\right\}\right)$ or express D directly as function of A i.e. $D = D(A)$. The first is considered here. The latter is considered elsewhere.

The first expresses all the *A*'s and the *D*'s of the objective function J_s, Eq. (6) in terms of their corresponding $\{V_{duty}\}$ and $\{V_{efficiency}\}$. $\{V_{duty}\}$ are variables at the boundaries of the device and $\{V_{efficiency}\}$ are local to the device.

Conventional thermodynamic computations usually assign $\{V_{efficiency}\}$ as the major part of the thermodynamic decision variables {Y} that are needed to obtain a solution. All dependent variables {X} follow by satisfying mass and energy balance equations. The result is that most of $\{V_{duty}\}$ are dependent variables and most $\{V_{efficiency}\}$ are decision variables.

Decomposition at the device level utilize the feature of this result as follows:

- Divide decision variables {Y} into local that permit decomposition and Global $\{Y_G\}$ that do not. $\{Y_L\}$ is a large set of mainly $\{V_{efficiency}\}$ decision variables. $\{Y_G\}$ is a much smaller set of $\{V_{duty}\}$ decision variables dealing mainly with design levels of pressures, temperatures and compositions.
- Apply Eq. (7) to optimize the system devices one by one with respect to the corresponding local decisions $\{Y_L\}$.
- Since the influence of $\{Y_L\}$ is not absolutely local, use the optimizing relations as updating relations converging to the optimal of the system.

Experimenting with this decomposition for an assumed positive set of $\{c_{di}\}$ showed fast successful convergence, thus verifying the above stated principle. The formulation *D* ($\{V_{duty}\}$, $\{V_{efficiency}\}$) corresponding to its *A* formulation is listed with the list of costing equations.

2.3.3 The Updating Equation

The objective function of a device is

$$J_i = c_{di} * D_i + c_{zi} * c_{ai} * A_i \qquad (11)$$

D_i and A_i are in conflict with respect to a local decision Y_{Li} expressed in general as η_i, i.e.

$$J_i = k_e * \eta_i^{ne} + k_m * \eta_i^{nm} \qquad (11a)$$

n_e and n_m are of opposite sign (a generalization of $J = a * \eta_i + b/\eta_i$). If the energy and material factors k_e and k_m were constants then the optimum is obtained in one system computation by the following analytical equation:

$$\eta_{i\,opt} = \left[-\left(k_m * n_m\right)/\left(k_e * n_e\right)\right]^{1/(ne-nm)} \qquad (12)$$

Because k_e and k_m vary mildly with local decision, substituting D_i and A_i for k_e and k_m, produces the updating equation for the convergence k_e and k_m to constants:

$$\eta_{i\,new} = \eta_{i\,old} * \left[\left(-n_m/n_e\right) * \left(c_{zi} * c_{ai} * A_i\right)/\left(c_{di} * D_i\right)\right]^{1/(ne-nm)} \qquad (13)$$

2.3.4 The Price of Exergy Destruction

The objective function of a device is

$$J_i = c_{di} * D_i + c_{zi} * c_{ai} * A_i \qquad (11)$$

The price of exergy destruction c_{di} depends on its location relative to other devices in the system. Eqs (5) and (6) give:

$$J_s = c_f * F + \Sigma c_{zi} * c_{ai} * A_i = {}_{i=1}\Sigma^n \left(c_{di} * D_i + c_{zi} * c_{ai} * A_i\right) \qquad (14)$$

hence

$$c_f * F = {}_{i=1}\Sigma^n \left(c_{di} * D_i\right) \qquad (15)$$

For a decision Y_i as a local decision of a device i:

$$c_f * \partial F\left(Y_i\right)/\partial Y_i = c_{di} * \partial D_i\left(Y_i\right)/\partial Y \qquad (16)$$

$$c_{di} = c_f * \partial F\left(Y_i\right)/\partial Y_i / \partial D_i\left(Y_i\right)/\partial Y \qquad (17)$$

$$= c_f * \left(\partial F/\partial D_i\right) \text{ by a small change in } Y_i \qquad (17a)$$

Thus an exergy destruction price is the fuel price modified by the sensitivity of fuel consumption to change in exergy destruction induced by change in an efficiency decision variable and is always positive. Experimenting with Eq. (17) gave always non-negative prices somewhere between the market place fuel price per unit exergy and the market-place prices (and not production costs) of the products per unit of their exergies. An average exergy destruction price often results in an improvement of the objective J_s thus allowing the use of one price for all exergy destruction as an option. However, searching for the maximum improvement around the value of the average exergy destruction price results in further improvement. A suitable average value for the general case of more than one fueling resource more than one product is:

$$c_{da} = \left(\Sigma c_f * F + \Sigma c_p * P\right) / \left(\Sigma E_f + \Sigma E_p\right) \tag{18}$$

2.3.5 Global Decision Variables

Few decision variables belong to the system as a whole and are considered global. Operating pressure and temperature levels of a system are examples of global decisions. Devices are not decomposed with respect to these decisions. A nonlinear programming algorithm may be invoked to solve for the optimum of these decisions simultaneously. If the range of variation of global decisions is narrow manual search may be sufficient. A simplified gradient-based method that ignores cross second derivatives at the expense of slow convergence may also be used. It has the following updating equation for a global decision Y_G:

$$Y_{G\,new} = Y_{G\,old} \pm \Delta Y \tag{19}$$

$$\Delta Y = ABS\left[.5 * \left(Y_{G2} - Y_{G1}\right) / \left(g_2 - g_1\right) * \left(-g_1\right)\right] \tag{19a}$$

$$g_1 = \left(J_o - J_1\right) / \left(Y_{Go} - Y_{G1}\right) \tag{19b}$$

$$g_2 = \left(J_2 - J_o\right) / \left(Y_{G2} - Y_{Go}\right) \tag{19c}$$

$$Y_{G2} > Y_{Go} > Y_{G1} \tag{19d}$$

The updating Eq. (19) requires 3 system computations to obtain three neighboring values of the objective function assuming for example Y_{Go}, 1.05 Y_{Go} and 0.95 Y_{Go}. The ± sign is supposed to be selected to direct the change in the favored direction because zero gradient represents both maximum and minimum. The process per decision is much slower compared to that of optimizing local decisions irrespective of their number.

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Bibliography

Cerqueira S. and Nebra S. (1999). Cost attribution methodologies in cogeneration systems. *Energy Conversion and Management* **40**, 1587–1597. [Other approaches to the costing exergy. Compare with exergy destruction costing used in this article.]

El-Sayed Y. and Aplenc A. (1970). Application of the thermoeconomic approach to the analysis and optimization of a vapor-compression desalting system. *Journal of Engineering for Power* 17–26

(January). [The start by an application.]

El-Sayed Y. and Evans R. (1970). Thermoeconomics and the design of heat systems. *Journal of Engineering for Power* 27–35 (January). [The start of Thermoeconomics.]

El-Sayed Y. M. (1993). Advances in the methodologies of optimal thermal design. *Desalination* **92**, 79–101. [For a convenient list of second-law analysis equations, see appendix.]

El-Sayed Y. M. (1996). A second-law-based optimization, Parts 1 and 2. *Journal of Engineering for Gas Turbine and Power* **118**, 693–703. [More details on Thermoeconomics, Design models for costing equations, an example list of costing equations and their trade-off with exergy destruction.]

El-Sayed Y. M. (1999). Revealing the cost-efficiency trends of the design concepts of energy-intensive systems. *Energy Conversion and Management* **40**, 1599–1615. [Generalized and derived off-design performance equations.]

El-Sayed Y. M. and Gogus Y (2000). Demand variability and mismatches in the cogeneration of power and process heat. *ECOS 2000,* 5–7 July 2000, University of Twente, The Netherlands. [More details of the stand-alone system for power, cooling and heating.]

Frangopoulos C. (1990). Intelligent functional approach: a method for analysis and optimal synthesis-design-operation of complex systems, *Proceedings of the International Symposium: A Future for Energy*, Florence, Italy: Pergamon Press, pp. 805–15. [Expanding the base of energy system analysis.]

Gaggioli R., ed. (1980). Thermodynamics: Second Law analysis. *ACS Symposium Series* 122. [The development of improved thermodynamic analysis.]

Gaggioli R., ed. (1983). Efficiency and Costing. *ACS Symposium Series* 235. [Building a bridge between thermodynamics and economics.]

Lazaretto A. and Tsatsaronis G. (1997). On the Quest for Objective Equations in Exergy Costing. *Proceedings of ASME Advanced Energy Systems Division,* AES **37**, pp. 197–210. [Costing exergy by an accounting approach.]

Linhoff B. (1994). The use of pinch analysis to knock down capital costs and emissions. *Chemical Engineering Progress*, August, 32–57. [The same target of thermoeconomics by a different approach, most useful for heat exchanger network.]

Sciubba E. and Melli R. (1998). *Artificial Intelligence in Thermal Systems Design*. Nova Scientific Publishers, 201 pp. [An expert system approach sharing the same target of thermoeconomics.]

Torres C., Serra L., Valero A., and Lozano M. (1996). The productive structure and thermoeconomic theories of system optimization, *Proceedings of ASME Advanced Energy Systems Division,* AES **36**, November, 1996, pp. 429–436. [Improving the foundations of thermoeconomics.]

Tribus M. and Evans R. (1962). The thermoeconomics of sea water conversion, *UCLA report No. 62-63,* August. [The birth of thermoeconomics.]

Biographical Sketch

Yehia El-Sayed started his own consulting company, Advanced Energy Systems Analysis, in 1987 in Fremont California USA. Before that Dr. El-Sayed, as Professor of Mechanical Engineering, had a teaching career that spanned over more than thirty years and over four educational institutes: Assuit University, Egypt; Tripoli University, Libya; Glasgow University, Scotland; Massachusetts Institute of Technology, Cambridge Massachusetts USA. Dr. El-Sayed has authored and co-authored more than 50 publications. His most recent publications are: *A Desalination Primer*, a book in 1994 with Professor K. S. Spiegler; *Repowering Second-Law-Based Optimization*, a paper in energy analysis that received the 1996 ASME Edward Obert Award; *The Thermoeconomics of Seawater Desalination Systems*, a paper that received the best paper presentation award at IDA'97 in Madrid, Spain. Dr. El-Sayed obtained his B.Sc. in Mechanical Engineering in 1950 from Alexandria University, Egypt, and his Ph.D. in 1954 from Manchester University, England. He became Professor in 1966 at Assiut University, Egypt and became a Fellow of the American Society of Mechanical Engineers in 1990.