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Thermoeconomic optimization method as design tool in gas–steam combined plant realization

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Abstract

In modern power plants design, not only high performances but also low capital investments have to be assured so that the final product proposed on the market could be competitive. Starting from this concept, in this work, we have realized a tool for a thermoeconomic evaluation and optimization of thermal power plants which could give solutions to problems connected with the design of real systems.

The model, using three programs and a set of cost correlations (obtained from collaboration with Nuovo Pignone–General Electric), can estimate the realization costs of a combined power plant as a function of the constructive and operation parameters. A test to verify the capacity of our model has been performed by simulating an existing plant. The results seem very good, and this tool will be soon used also in the industry.

Keywords: Thermoeconomic analysis; Energy conversion system; Cost correlations; Optimisation process

1. Introduction

The design of a modern power plant means to realise a product with a low investment cost but a high efficiency. Thermoeconomic analysis represents a very important tool for the thermal systems designer to determine the optimal configuration for a new system or to plan changes on an existing one. In this work, the model realised allows a thermoeconomic optimisation of thermal systems. The simplicity of the solving procedure and the strong link with the real problems involved in power plants design are the main features of this model.

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Nomenclature

A	steam turbine final section (m^2)
HP	high pressure
LP	low pressure
C	cost (purchase, management, operation) (US$)
F	cash flow
FO	objective function
gg	plant annual operation days
i	interest rate
INV	investment
k_a	ammortized capital fraction
k_p	borrowed fraction of capital investment
MARR	minimum attractive rate of return
n	power plant technical life
Pot	power plant overall power (W)
Q	heat (W)
S	heat exchange surface (m^2)
T	temperature (K)
TET	outlet turbine temperature (K)
TIT	inlet turbine temperature (K)
TR	tax rate
W	device power (W)

Greek

η	efficiency

Subscripts

(comp)i	generic plant component
purc	purchase
ins	insurance
CC	combustion chamber
civ	civil works
comb	fuel
Comp	compressor
Cond	condenser
HRSG	heat recovery steam generator
lavO&M	personnel work
LTE	feed water pre-heating
O&M	operation and maintenance
Pcond	condenser pump
piping	plant piping
TAG	gas turbine
TAV	steam turbine

All our work is based on cooperation with Nuovo Pignone whose economic data and consultancy have been fundamental for the cost correlations development of the ‘‘major components’’ of a combined power plant. This cooperation, together with the simulation and optimisation codes developed in these years inside the energetic department, has allowed us to develop an original approach to thermoeconomy. As we will be able to see later in this paper, our approach is quite different from those present in the literature [3,6].

2. Simulation programs structure and features

2.1. General model features

The solving procedure works by running three programs at the same time:

- the ESMS which is a FORTRAN program, simulating power plant performances. It has been already developed at the energetic department [1,2];
- the (research of optimum on continuous parameters) Ropac which represents the optimisation program (it is a Visual Basic program) developed just for this work, and

- the interface program OPTI which calculates economic functions selected to be optimised.

The Ropac's aim is to calculate the maximum (or minimum, depending on the function) value of a selected economic function depending on thermodynamic and constructive parameters of the system.

The ESMS simulates plant performances: it allows us to simulate any energy system simply by joining the right components (the program "sees" them as modules) by supplying a sufficient number of informations on each module and the boundary conditions. It is not important which information we supply but only their number and their independence of each other. As result, we get a set of values for pressure, mass flow rate, temperature and other thermodynamic parameters in all the points of the thermodynamic cycle.

So, the optimisation procedure is executed by means of the following steps: the Ropac continuously runs ESMS and OPTI; each time, the interface program (OPTI) reads in the output files of ESMS the parameter values, and so, it calculates the objective function previously selected and stores the calculated points in Ropac. At this point, the optimiser (Ropac) supplies new input values to ESMS based on its optimisation algorithm (the selected one or the selected combination between genetic, complex, random), and the cycle begins again. At the end of the procedure, Ropac supplies the maximum (or minimum) value of the objective function and the thermodynamic parameters chosen as independent variables for the simulation. Using ESMS to simulate plant performances, we can overcome a problem of classic thermoeconomic theories [3]. The first step for a thermoeconomic analysis, in fact, is the choice of the independent variables set, and it is not easy to determine a set of linearly independent variables which are significant for the examined system. Using ESMS, there is not this kind of problem because it can correctly run only if input variables are linearly independent of each other. This means that the problem is limited to ESMS: once the right parameters are located for it, the procedure can go on without other problems.

2.2. The Ropac program

Ropac has a high applicability and assures a very flexible use. The principal aim in the program features was to provide a simple optimisation tool for every kind of energetic system simulation code.

Ropac uses the simulation program (ESMS in our case) as a blackbox which only has to attend to the calculations of the thermodynamic parameters by processing a set of input variables, Ropac has no concern about the inside structure of that program.

The program leads to the optimisation by continuously running the simulation code and deciding the new values for the new input variables by using its evolutionary techniques. The genetic procedure [8], for example, makes an investigation of the "calculated points populations", selects some of the best individuals of the "population" and makes the crossover among them. The program lets the number of generations be selected, avoids the crossover among "relatives" (which are points with a very similar set of input variables) and excludes from the following generation the "supermans" by scaling the excessively good points. In this way, the procedure, in the "same" way followed by nature to assure the species evolution, leads to the optimal solution for the problem.

2.3. The OPTI program

This program was developed to link thermodynamic simulation with economic parameters and correlations. The program is the interface between Ropac and ESMS, and its structure can be divided into three parts: a first part which reads from two external data files some general parameters for the plant devices and the kind of objective function; a second part which reads from ESMS output files coming from the simulation and calculates the economical parameters (such as costs, objective functions etc.) using those informations, and a third and last section which writes in two files the values of the objective functions and of the major components purchase costs, so they can be available for Ropac.

3. Objective functions

The most important element of our model is represented by the cost correlation set by means of which we calculate investment, operation, maintenance and management costs for the combined power plants as a function of thermodynamic and geometric parameters. Whatever is the chosen economic objective function (FO), this always will depend on the purchase cost of "major components", operation and maintenance costs and so on. In other words, every FO can be expressed by the generic relation:

$$\mathrm{FO} = f\left(\sum_{i=1}^{n}(C_{\mathrm{comp}})_i, C_{\mathrm{Piping}}, C_{\mathrm{O\&M}}, C_{\mathrm{comb}}, C_{\mathrm{lavO\&A}}, C_{\mathrm{civ}}, C_{\mathrm{ins}}, R_{\mathrm{p}}\right) \tag{1}$$

where $\left(\sum_{i=1}^{n} C_{\mathrm{comp}}\right)_i$ is the purchase cost for the i component of the n components of the system, C_{Piping} is the piping expense for the plant, $C_{\mathrm{O\&M}}$ are "operation and maintenance" costs, C_{comb} is fuel expense, $C_{\mathrm{lavO\&A}}$ is annual personnel expense, C_{civ} is civil works cost, C_{ins} is insurance cost, R_{p} is the income coming from products (electric energy or cogeneration heat) sold.

In the following are described the objective functions that can be used by our model:

net actual value (VAN) of the investment:

$$\mathrm{VAN} = \sum_{j=0}^{n} F_j \left(\frac{1}{1+i}\right)^j \tag{2}$$

internal rate of return (IRR), that is:

$$\mathrm{VAN(IRR)} = 0 \tag{3}$$

annual equivalent (AE) of the investment:

$$\mathrm{AE} = (R_{\mathrm{P}} - C_{\mathrm{comb}} - C_{\mathrm{O\&M}} - C_{\mathrm{comb}} - C_{\mathrm{ins}} - C_{\mathrm{lavO\&A}}) - \mathrm{INV}\left(\frac{(\mathrm{MARR}+1)^n \mathrm{MARR}}{(\mathrm{MARR}+1)^n - 1}\right), \tag{4}$$

annual cash flow for the plant:

$$\mathrm{FC} = \left\{ \left[R_{\mathrm{P}} - C_{\mathrm{comb}} - C_{\mathrm{O\&M}} - C_{\mathrm{comb}} - C_{\mathrm{ins}} - C_{\mathrm{lavO\&A}} - k_{\mathrm{a}} \left(\frac{\mathrm{INV}}{n} \right) \right] (1 - \mathrm{TR}) \right\} + k_{\mathrm{a}} \left(\frac{\mathrm{INV}}{n} \right) - k_{\mathrm{p}} \mathrm{INV} \frac{(i+1)^n i}{(i+1)^n - 1} \quad (5)$$

unit product cost:

$$C_{\mathrm{pu}} = \frac{\mathrm{AE}}{24\mathrm{ggPot}} \quad (6)$$

purchase cost of the plant major components:

$$C_{\mathrm{purc}} = \sum_{i=1}^{n} \left(C_{\mathrm{comp}} \right)_i \quad (7)$$

Each function has to be expressed as a function of technical and operational parameters because, only in this way, will it be possible to do a thermoeconomic analysis of the system. The variable $\left(\sum_{i=1}^{n} C_{\mathrm{comp}} \right)_i$ is the most important to correlate but also the most complex because it requires the development of as many correlations as the number of plant components (major components). Thanks to the cooperation with Nuovo Pignone, we could have a lot of real cost data of plant components. Fitting these data and by choosing appropriate mathematical expressions [4,5,7], we have developed a set of correlations for calculating the purchase costs of the combined power plant major components.

The other variables ($C_{\mathrm{O\&M}}$, $C_{\mathrm{lavO\&A}}$, C_{civ} etc.) can be expressed as a capital investment percentage of the system, and for this reason, they need a lower number of data.

4. Component capital costs functions

A very important step for the development of our optimization model was the development of component capital cost functions. For some devices, correlations suggested in Refs. [4,5,7] have been updated on the basis of Nuovo Pignone cost data, but for other components (such as gas turbine, steam turbine and condenser), we have developed completely new formulations based on technical and design considerations.

In Table 1 are presented our cost functions for the major components of a combined power plant.

The cost functions give net capital costs of the components (“lower costs”), and their coefficients do not take into account transport and assembly costs, assembly supervising, accessories, engineering and project management. These additional costs can be calculated as a percentage (p_k) of net cost, so that the real device cost can be written as:

$$\left(C_{\mathrm{comp}} \right)_i = (1 + p_1 + p_2 + p_3 + p_4 + p_5) C_{\mathrm{correlation}} \quad (8)$$

Table 1
Devices cost functions

Component	Function
(1.2) Multi-level HRSG	$C_{\mathrm{HRSG}} = 17000\left[\sum_{i=1}^{n}\left(\frac{\dot{Q}_{\mathrm{econ}}}{\Delta T_{\mathrm{econ}}}\right)_i^{0.6} + \sum_{i=1}^{n}\left(\frac{\dot{Q}_{\mathrm{evap}}}{\Delta T_{\mathrm{evap}}}\right)_i^{0.6} + \sum_{i=1}^{2}\left(\frac{\dot{Q}_{\mathrm{sh}}}{\Delta T_{\mathrm{sh}}}\right)_i^{0.6} + \left(\frac{\dot{Q}_{\mathrm{LTE}}}{\Delta T_{\mathrm{LTE}}}\right)^{0.79}\right]$
(2) Gas turbine	$C_{\mathrm{TAG}} = 3832W^{0.71}$
(3) Steam turbine	$C_{\mathrm{TAV}} = 3\,197\,280A^{0.261} + 823.7W^{1.543}$
(4.1) Titanium condenser	$C_{\mathrm{Cond}} = 17\,769S^{0.516}$
(4.2) Copper–nickel condenser	$C_{\mathrm{Cond}} = 2296S^{0.79}$
(4.3) Alluminium–brass condenser	$C_{\mathrm{Cond}} = 162S^{1.01}$
(4.4) Stainless condenser	$C_{\mathrm{Cond}} = 1.7(162S_{\mathrm{eq}}^{1.01})$
(5.1) Condenser pump	$C_{\mathrm{P.Cond}} = 37.6W^{0.8}\left[1 + ((1-0.7)/(1-\eta_{\mathrm{iso}}))^{-0.46}\right]34.4$
(6) Generator	$C_{\mathrm{ALT}} = 3082W^{0.58}$

5. The simulation of an existing power plant with our model

It was important to test our correlations and our programs by the thermoeconomic analysis of an existing system. The Nuovo Pignone gave us the case of study by proposing a two pressure levels combined power plant they were selling to a client.

The functional diagram of the system is shown in Fig. 1. The gas turbine chosen is the General Electric MS6001FA. Its technical features are presented in Table 2. Table 3 shows the values fixed by the design operation configuration for steam quality (pressure and temperature), high and low pressure cogeneration steam mass flow rate and overall plant power.

HRSG pinch points, high pressure steam temperature, high pressure level, condenser and deareator pressures are "free" variables for the plant. The selected FO for the optimisation is $C_{\mathrm{purc}} = \left(\sum_{i=1}^{n} C_{\mathrm{comp}}\right)_i$, and it has been expressed as a function of the following independent variables:

1. High pressure steam temperature (Tvsrhp)
2. Topper pressure level (Pvhp)
3. Reheat pressure (PvRH)
4. High pressure pinch point (ppHP)
5. Low pressure pinch point (ppLP)
6. Condenser pressure ($\mathrm{P_{cond}}$)

Therefore, the generic formulation for the objective function to minimise is:

$$C_{\mathrm{purc}} = C_{\mathrm{purc}}(\mathrm{Tvsrhp}, \mathrm{Pvhp}, \mathrm{PvRH}, \mathrm{ppHP}, \mathrm{ppLP}, \mathrm{Pcond}) \tag{9}$$

The six independent variables are not completely free because there are technological limitations fixed by constructive materials and operational conditions of the components. This is not a problem for our model because it can set bounds for any parameter directly inside the Ropac program. What's more, a minimum value for plant efficiency has been introduced in the OPTI program so that it could not accept solutions with low C_{purc} but bad efficiency.

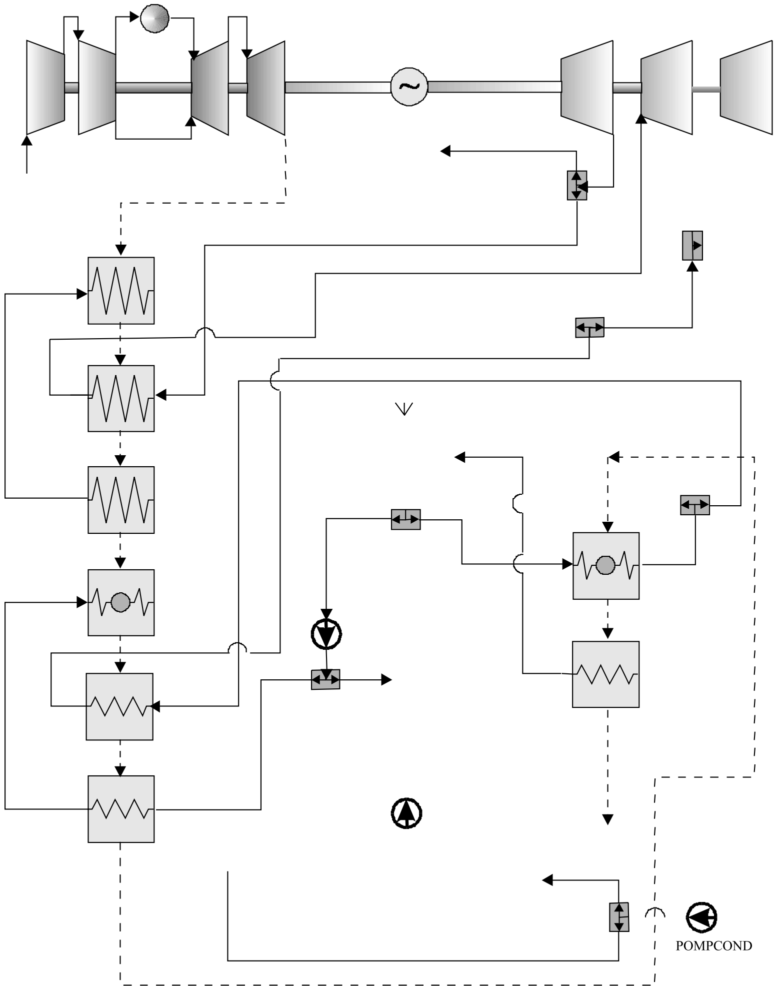

Fig. 1. Functional diagram of a system.

Table 2
MS6001FA gas turbine main features

Mass flow rate (kg/s)	β	TIT (°C)	TET (°C)	RPM	Power (kW)	Heat rate (btu/kW h)
196.2	14.8	1287	597	5100	71 750	9740

Table 3
Design operation conditions

Overall plant power	100 MW
Cogeneration steam BP	9 bar, 220°C
Cogeneration steam AP	36.2 bar, 420°C

Table 4
Comparison between ESMS and Nuovo Pignone simulations results

Parameters	ESMS	Nuovo Pignone
Mfr lp steam	5.27 kg/s	5.35 kg/s
Mfr hp steam	26.4 kg/s	26.3 kg/s
Tag net power	69 995 kW	69 712 kW
Tav net power	38 100 kW	37 500 kW

The first step of our analysis has been the thermodynamic simulation of the plant by using the ESMS program. The results of the simulation, even if we have only fixed a few parameters of the plant, have been very close to those obtained by Nuovo Pignone by using their simulation code. Table 4 shows the comparison between ESMS values for some of the most important parameters and those estimated by the Nuovo Pignone engineers.

Figs. 2 and 3 compare the HRSG temperature curve calculated by ESMS and Nuovo Pignone, both for hot gas and steam. As we can see, the ESMS temperatures are very close to those calculated by Nuovo Pignone for the design configuration of the plant.

The results of the economic analysis are presented in Fig. 4 where capital costs of the major components and of the overall plant in the A configuration, which is the Nuovo Pignone commercial choice (based on the experience of other similar plants), and in the B configuration, which is the calculated one, have been compared.

As can be seen, the savings for the B configuration are near 4–5%. It is important to note that the purchase costs in the A configuration, which have been calculated with our functions, are very similar to those proposed by Nuovo Pignone to their client (correlation makes the mistake lower than 5%), and this is a very important confirmation of their value.

It is, moreover, interesting to note that the six optimal values of the independent variables calculated by our model are very close to those chosen by Nuovo Pignone (A configuration). This is a very important result and confirms our work, because the A configuration was the result of

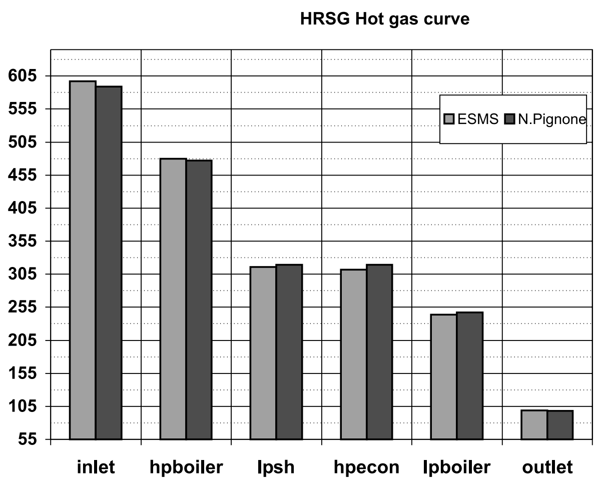

Fig. 2. HRSG hot gas curve.

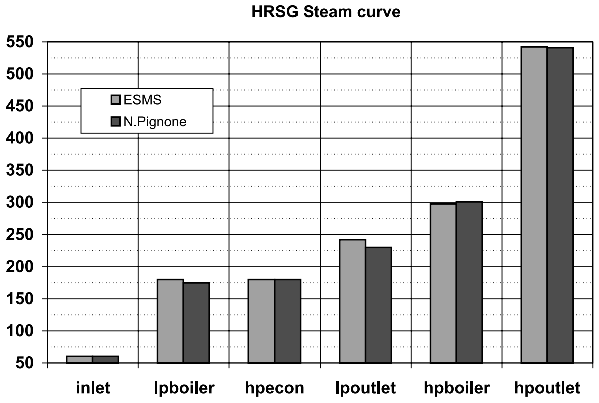

Fig. 3. HRSG steam curve.

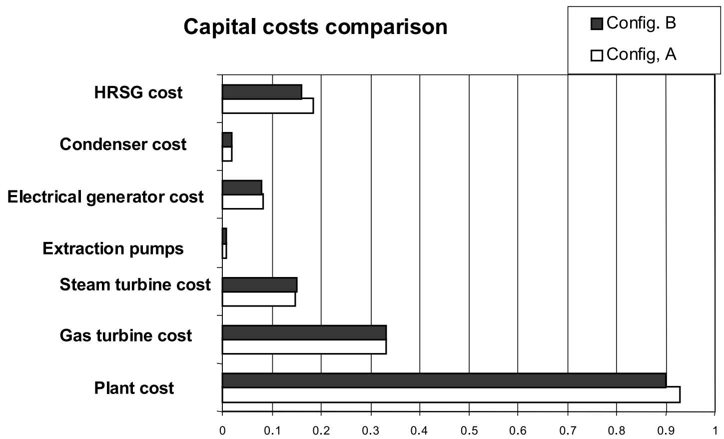

Fig. 4. Capital costs comparison.

the Nuovo Pignone many years of experience about plants design, and so, it had to be a good solution by itself.

6. Conclusions

This work shows that the thermoeconomic analysis requires an accurate thermofluidynamic analysis if it wants to propose itself as a valid tool in the design of modern power plants.

The approach and the methodology developed seem to provide good support in the cost plant definition, and the developed tool replies to the requests of good accuracy together with high speed and flexibility.

In this sense, the Nuovo Pignone support has been very important to understand the real industry needs and to verify our models.

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