OPTIMAL DESIGN OF COMBINED POWER, REFRIGERATION AND HEATING SYSTEM

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ABSTRACT : *To study of design energy systems, thermodynamics is commonly used, through-exergy analysis (E.A.) that allows identification of exergy losses along all parts of the system*

- *entropy generation minimisation (E.G.M.) to minimize the losses with specified constraints for the system studied*
- *thermo economy (T.E.) to minimize, investment or global costs of the system.*

Preliminary study of an energy system can be done, without knowledge of internal design of the system, taking only into account interactions of it with environment and external parts. Even in that case, physical constraints must be accounted for (maxima of temperature for materials, limitations of HEX dimensions, ...).

In this study, we will first report from a thermodynamical model of a trigeneration system, with finite size of H.E.X. (Heat Exchangers). Optimization of the system is reported through two parameters defined as ratios of cold and hot useful heat fluxes relative to useful mechanical power (these two ratios are related to the need expressed by the user of the system).

The energy optimization is related to the possible maximum of the mechanical power. An other objective function is to maximise the total value of all the produced energy (cold, hot, mechanical). Another step is to consider not only exergetic value, but financial and (or) environmental one. The proposed analysis allows all these developments.

A special attention is also devoted to interaction of the system with external parts (particularity at HEX). The influence of internal irreversibility is globalized ; but a careful analysis of each internal components could be done in the future, to extend the present proposed optimization.

Numerical results of the analysis are compared to some limit configurations allowing analytical results (trigeneration systems consisting of tow CARNOT machines : one engine, one receptor). A tentative comparison to some existing systems will also be proposed.

RESUME : *Dans l'étude d'un système thermodynamique, que ce soit dans un but de conception ou dans un but d'analyse, les plus récents développements utilisent conjointement l'analyse exergétique (EA) pour identifier les parties du système responsables des pertes thermodynamiques, la minimisation de génération d'entropie (EGM) pour minimiser les pertes sous l'influence des contraintes imposées au système, ainsi que la thermoéconomie (TE) pour minimiser les coûts de construction et de fonctionnement du système [1].*

L'étude préliminaire d'un tel système peut être effectuée sans tenir compte de sa conception interne, simplement en évaluant ses interactions avec l'extérieur (l'environnement). Néanmoins, de tels systèmes sont sujets à des contraintes d'ordre physique (dimensions des échangeurs, températures maximales supportées par les matériaux ...) qui sont autant de contraintes reliant le système et son environnement.

Dans cette étude, on va s'intéresser tout d'abord au comportement global d'une installation de trigénération, à l'aide de la thermodynamique en temps fini, qui seule peut rendre compte de l'influence des contraintes spatiales des échangeurs. Cette étude d'optimisation sera conduite selon une méthode spécifique : en effet, les ratios reliant les productions de froid et de chaleur « intermédiaire » au travail mécanique produit seront supposés connus et fixés. Cette configuration peut, par exemple, être le résultat des besoins exprimés par l'exploitant de l'installation.

L'objectif de l'optimisation revient alors à maximiser l'une des quantités produites, les autres en étant dépendantes. Un autre objectif envisageable est de maximiser la valeur totale des énergies produites. Mais, pour ce faire, il convient de définir les différentes valeurs d'une unité d'énergie produite, selon sa catégorie (froid, chaud, mécanique). Ces valeurs peuvent être financières, exergétiques ou environnementales, voire un assemblage des trois. Néanmoins, la conduite de l'analyse effectuée ici reste valable.

L'entropie générée par l'interaction entre le système et l'extérieur sera localisée aux échangeurs, l'influence de la génération interne d'entropie étant étudiée de manière globale, le système étant considéré irréversible. Là encore, seule l'étude des composants internes au système permettrait de définir ce paramètre, pour ensuite «remonter» à l'optimisation étudiée ici.

Ensuite, sera développée une configuration particulière d'une installation de trigénération, couplant deux cycles de Carnot (l'un moteur, l'autre récepteur). Les résultats numériques de l'analyse seront confrontés aux résultats analytiques connus.

KEYWORDS : *Optimal design, combined system, power, refrigeration, heating, finite size thermodynamics, congeneration, trigeneration.*

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1. INTRODUCTION

1.1 Mechanical (or electrical) power production

Until now [1] seems that the great majority of the studies has been concerned with power production (mechanical electrical) ; historically, it is the first need ; last tendencies in the field are directed toward exergetic optimization of electrical plant [2], or to economical aspects [3], or environmental consideration [4].

I.2 Cogeneration : heat and power

More recently, interest for joined production of heat and power has been recognized [5] : for hospital [4, 7] ; for university campus [7, 8]. Comparison of various cogeneratoin systems (gas turbine, diesel engine, fuel cell) has been done [9] on the basis of exergetic efficiency, and electrical ratio ; comparison of GRASSMANN exergetic efficiency of KALINA cogeneration system with RANKINE cogenerationsystem [10], has been done too. The same GRASSMANN method has been applied more extensively for cogeneration systems using combined and integrated cycles [11]. The last tentative seems to be finite time cogeneration model with a fixed ratio between heat and power [12].

1.3 Cogeneration : cold and power

It is the symetrical situation of the preceding regarding the ambiant temperature ; but it is less easier, because it does not fit with the natural evolution of the calorific energy in the system : it imposes at least a virtual three reservoirs heat receptor, or for example an absorption refrigeration machine [13, 14] ; the general corresponding scheme given in ref [15] does not precise anyway the configuration of the used refrigeration system. This paper supposes only a finite geometry, and gives the optimal allocation of heat transfer areas depending particularly on exergetic efficiency and ratio of refrigerating flux to power.

1.4 Three generation : heat, cold and power

We need currently in fact, heat, cold and power for example in houses and building, and in industry (food industry particularly). R. LAZZARINI and A. GASPARELLA [16] think to apply this for deshumidification ; S. DHAR MADHIKARI [17] for applicaiton to petrochemistry. P.S. PAN, Y. SUZUKI [18, 19] apply exergy analysis to a three generation system with a gas turbine for a district heating and cooling (in fact, it seems more a heating district). HAVELSKY work [20] is really a three generation system : the main conclusion is based on P.E.R. primary energy rate, that can be minimised.

1.5 The present paper

All the preceding references, allow us to say that until now, a finite time model of a heat-cold-power producing system does not exist. Using two ratios, we propose here to developp such a model, that can be useful to help in the design. The use of ratios allows us to compare with previous work, and to go further to them [12, 15, 20].

2. FINITE TIME MODEL OF THREE GENERATION SYSTEM

1.1 Schematic representation and hypothesis

The major hypothesis with Figure 1 are the following :
HYP.1, sources and sinks are considered thermostats
HYP.2, system is in a stationnary state (ratios are constant parameters)
HYP.3, heat transfer at sources and sink are supposed linear one.

2.2 Model's equations

Heat and cold ratios are expressed with respect of the useful power :

$$R_i = \dot{q}_i / \dot{w} \tag{1}$$

$$R_f = \dot{q}_f / \dot{w} \tag{2}$$

The heat transferred between a source (or sink), and the cycled medium are represented by the NEWTON law of heat transfer :

$$\dot{q} = K\,(T_S - T) \tag{3}$$

First law of thermodynamics indicates that :

$$\dot{q}_c + \dot{q}_i + \dot{q}_o + \dot{q}_f + \dot{w} = 0 \tag{4}$$

Second law of thermodynamics results in :

$$\frac{\dot{q}_c}{T_c} + \frac{\dot{q}_i}{T_i} + \frac{\dot{q}_o}{T_o} + \frac{\dot{q}_f}{T_f} + \dot{s}_i = 0 \tag{5}$$

2.3 Nondimensionnal variables and equations

The reference choosen flux is $\dot{q}_c$; so non dimensional fluxes are expressed as :

$$q = \dot{q}/\dot{q}_c \qquad w = \dot{w}/\dot{q}_c \qquad (6), (7)$$

The reference choosen temperatures is T_{SO} ; the choice of $\dot{q}_c$ as reference flux has been choosen to be consistent with results of [15], and to compare the results, but we mention that this reference suppose $\dot{q}_c$ imposed in fact. So it comes :

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$$1 + (1 + R_i - R_f)\, w + q_o = 0 \qquad (8)$$

$$\frac{1}{T_C} + \left(\frac{R_i}{T_i} - \frac{R_f}{T_f} \right) w + \frac{q_o}{T_o} + \frac{\dot{s}_i}{\dot{q}_c} = 0 \qquad (9)$$

we seek in that case for the maximum of w, with the following associated constraints :

$$q_o = k_o\, x_o \qquad (10)$$

$$k_T = k_c + k_i + k_f + k_o \qquad (11)$$

$$R_i \frac{T_{so}}{T_{si}} w = k_i\, x_i \qquad (12)$$

$$R_f \frac{T_{so}}{T_{sf}} w = -k_f\, x_f \qquad (13)$$

$$\frac{T_{so}}{T_{sc}} = k_c\, x_c \qquad (14)$$

with the following non dimensional variables

$$x_j = \frac{T_{sj} - T_j}{T_{sj}} \qquad (15)$$

$$x_j = \frac{K_j \,.\, Tso}{\dot{q}_c} \qquad (16)$$

formulas (10, 14) give k_j variables in function of X_j variables ; combining with (8, 9), it comes the w objective function, with one constraint on the x_j variables. Numerical calculations has been performed with MATLAB.

Before to consider the results obtained, some comments ; we adopt here the same approach as given in [15] ; so we introduce the same exergetic efficiency as in [15] (for cold cogeneration only) ; the exergetic efficiency η_{IIi} is defined as the ratio of **exergy associated to exiting energy** (different of exiting exergy) on **exergy associated to entering energy** (different of entering exergy) ; so it differs from GRASSMANN definition. We conserve this for comparison purpose, but notice carefully that :

$$\eta_{IIi} = 1 - \frac{s_i}{1 - \frac{T_{so}}{T_c} + q_f \left(1 - \frac{T_{so}}{T_f} \right)} \qquad (17)$$

So it appears that entropy analysis (with si) is more powerful, due to the fact that η_{IIi} depends on variable temperatures of the system (as η_{exi}, exergetic intrinsec efficiency) ; opposite to that we can easily see that total exergetic efficiency η_{ext}, is preferable, due to the fact that it depends only on thermostats temperature and s_t, reduced total entropy flux. It will be done in future works envisaged.

3. SOME RESULTS EXAMINED

We will only due to page limitation illustrate the sensitivity analysis done, for the main parameters. To be consistent with [15] we choose as objective w, in function of reduced temperatures τ_j, τ_{sj}, and reduced equivalent heat transfer units x_j, respectively expressed as :

$$\tau_j = \frac{T_j}{T_{so}} \quad ; \quad \tau_{sj} = \frac{T_{sj}}{T_{so}} \quad ; \quad x_j = \frac{N_j}{N_T}$$

The sensitivity study has been done near of the central values of the following parameters vector : {$R_i = R_f = 1$; $N_T = 5$; $\tau_{sc} = 4$; $\tau_{si} = 1{,}5$; $\tau_{sf} = 0{,}9$; $\eta_{IIi} = 0{,}70$)

3.1. Sensitivity to the total NUT to be allocated

Figure 2 illustrates the influence of N_T, on the allocation of areas between the various HEX. It appears a thresh old for a given N_T value, that corresponds to total dissipation of disponible energy. W_{max} increases asymptotically with N_T. correspondingly, it has been seen, that optimum pinches increase according to the level of temperature of source or sink.

3.2. Sensitivity to R_i and R_f ratios (Figures 3 and 4)

R_f and R_i ratios have apposite and strong influence on xf_{opt} and xi_{opt}. When $R_f \rightarrow 0$ (hot cogeneration) or $R_i \rightarrow 0$ (cold cogeneration) the corresponding limits tend to preceding obtained results [15]. The same study has been done for optimum pinch at the HEX ; the corresponding results are disponible near the authors, for brievety.

3.3. Discussion of results

The parametric study exposed here confirms and extends the results obtained in [15] for cold cogeneration. However it has been pointed out some improvments actually developped of this same work [15].

The whole sensitivity analysis could be published in the future. The reported model supposes the heat flux at the source imposed as a reference ; other configurations are possible ; they are actually developped analitycally and numerically.

4. CONCLUSIONS

This paper deals with the first three generation model from a finite time thermodynamics point of view. Original results completing preceding ones obtained for cold cogeneration as a limit cases are obtained and discussed on a constructive way.

Influence of the R_i and R_f ratios values have been examined ; this could be helful for the design of such a system. Optimization could be pursned taking account of economic aspects, or environnomic aspects ; this will be considered in the future.

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Nomenclature

R, ratio
$\dot{q}$, heat flux
$\dot{w}$, mechanical power
T_s, source or sink temperature
T, cycle medium temperature
K, heat transfer conductance
$\dot{s}$, entropy flux
q, non dimensional heat flux
w, non dimensional power
x, non dimensional pinch or nut
k, non dimensional heat transfert conductance
η, efficiency
τ, reduced temperature

Index

c, hot
i, intermediate, internal
o, ambiant
f, cold
s, source, sink
T, t, total
II, second principe
ex, exergetic

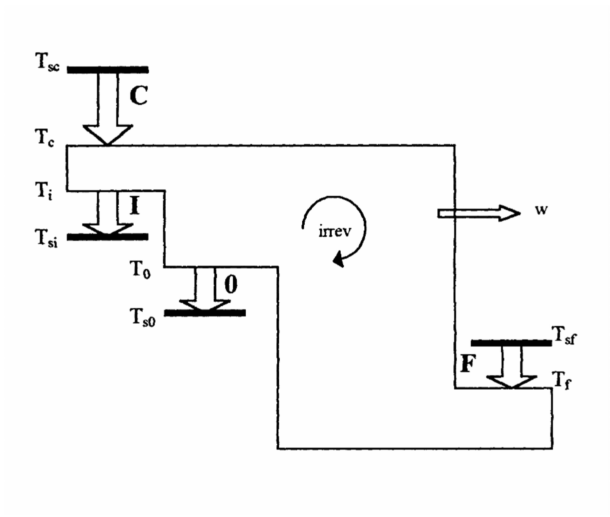

Figure 1 : Shematic of a three generation process

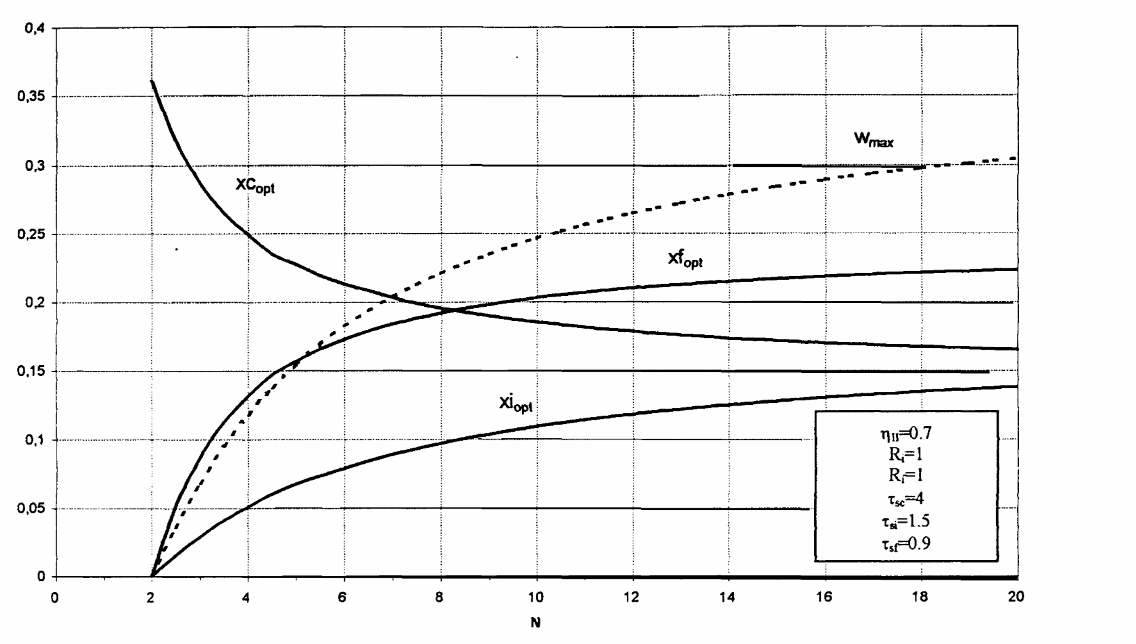

Figure 2 : Optimal allocation of areas in function of total NVT available

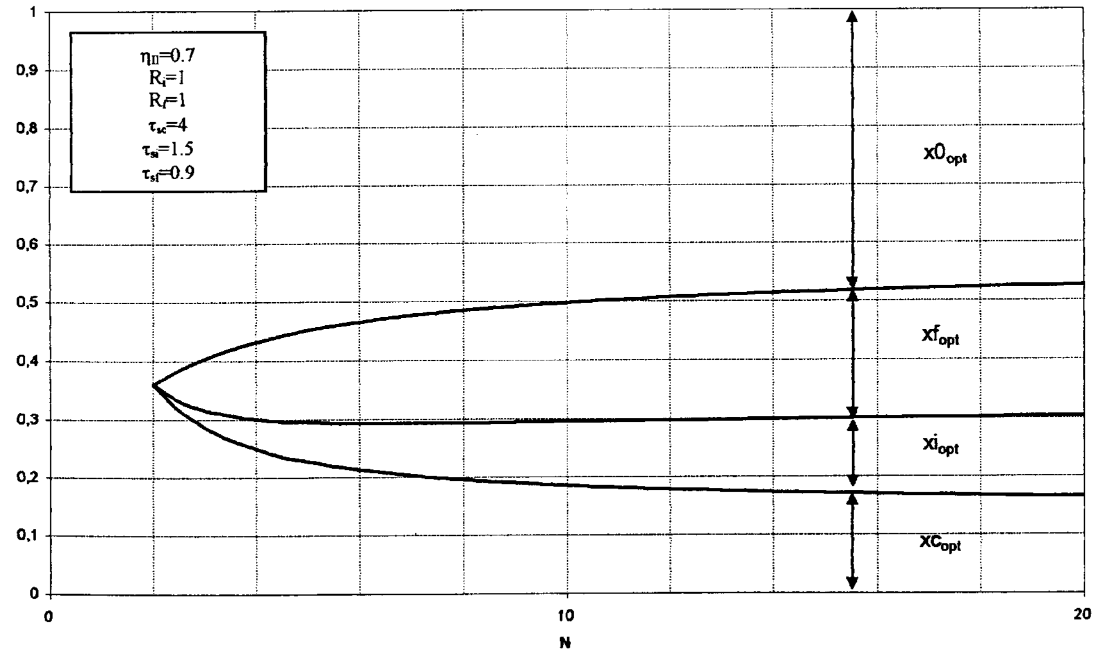

Figure 3 : Optimal allocation of areas in function of R $_f$ ratio

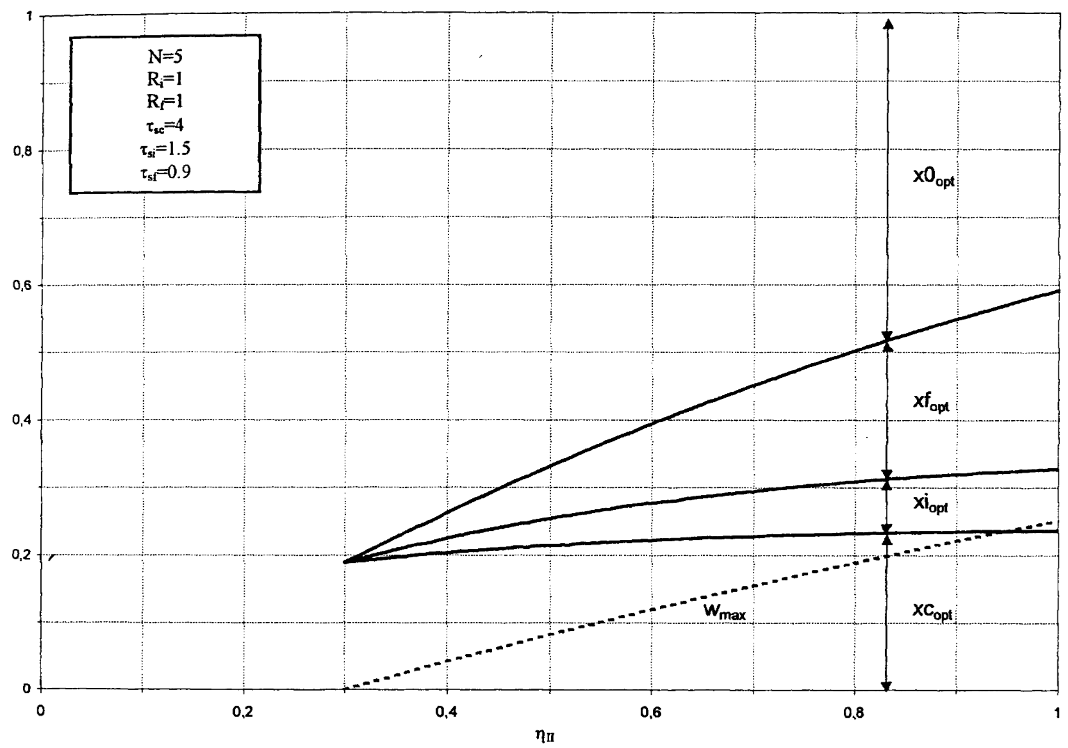

Figure 4 : Optimal allocation of areas in function of R $_i$ ratio