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On the use of process integration techniques to generate optimal steam cycle configurations for the power plant industry.

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The integration of steam cycles in the power plant industry aims at optimizing the conversion of the available heat into mechanical power. The proposed method uses process integration techniques and a multi-objective optimisation procedure to generate optimal steam cycle configurations which can be ordered by complexity-costs and efficiency. The interest of this methods is to allow the integration of complex heat exchanger network layout, providing systematically alternative arrangements using an effective solving method.

Keywords: steam network, multi-objective optimisation, power plant design

1 Introduction

The developpement and improvement of power plants is a more and more complex task that require the integration of modularized energy system with optimal efficiency, cost and emission performances[6]. For example, in new advanced power plant designs with CO2 capture, the integration of the steam cycle has to be adapted in order to account for the different hot and cold streams that result from the CO2 capture devices that are used at different temperature levels.

If steam network synthesis procedure are reported in the literature([2], [8] and [7]), the interest of the proposed method is to allow the estimation of the performances of complex and higlhy integrated heat exchanger network layout.

The two objectives considered are the steam network cost and the power plant power output. This approach also allows the simultaneous optimisation of the power plant operating conditions. In this paper, the steam cycle modeling method is validated by solving a conventional natural gas combined cycle(NGCC) power plant.

2 Mathematical model of the steam network

Following the work of[7], the steam cycle model is build from of a list of steam headers that are interconnected to create a superstructure shown on figure (2). The super-

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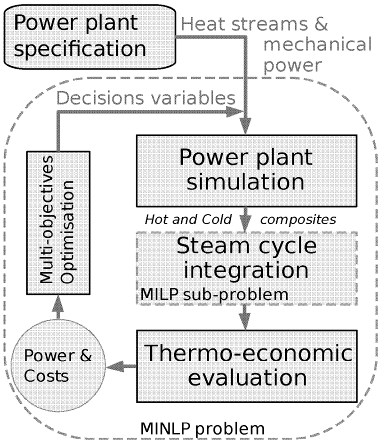

Figure 1: Two level strategy for the resolution of the MINLP problem.

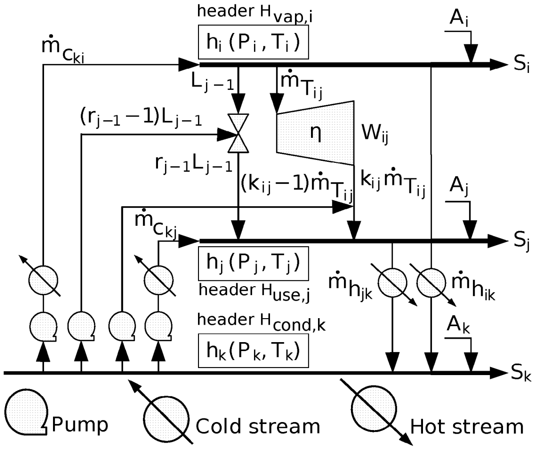

Figure 2: Superstructure of a steam network with one expansion level.

structure is generated from the definition of 3 types of headers: the steam production header(H_{vap}), the steam usage header(H_{use}) and the condensation header(H_{cond}) that defines the liquid state. Each steam header is defined by its pressure level and specific enthalpy $h(x,T,P)[J/kg]$.

2.1 Estimation of the size and complexity of the heat exchangers network

Assuming a minimum approach temperature between hot and cold streams, the composite curves[4] allow to compute the heat recovery and to estimate the area and the cost of the heat exchanger network. This method is used to model the heat exchanger between the steam cycle streams and the other streams of the power plant.

2.2 Hot and cold streams

The superstructure is made of hot streams that corresponds to steam extraction with desuperheating and condensation. The cold streams corresponds to steam production including pre-heating, evaporating and eventually superheating section. When the pressure of a level is higher than the pressure of another and the enthalpy of first is lower than the pressure of the other, then a reheating heat exchanger is introduced from the first to the second.

2.3 Mechanical work

The mechanical work($\dot{W}_{i,j}$) is produced by expansion $\dot{m}_{T_{ij}} \cdot w_{ij}$ between production($h_{vap,i}$) and usage header($h_{use,j}$). It is computed by equation (1) with the isentropic efficiencies($\eta_{k,k+1}$) calculated from[3] by $0.919 - 0.549 \cdot (1 - \frac{P_k - P_{k+1}}{P_k})$ and considering multistage turbines between each intermediate pressure levels.

$$w_{ij} = \eta_{i,i+1} \cdot (h_i - h_{is}(P_{i+1}, s_i)) + \sum_{k=i}^{j-1} \eta_{k,k+1} \cdot (h_{k-1} - w_{k-1,k} - h_{is}(P_{k+1}, s_k)) \qquad (1)$$

If the obtained power is greater than the fixed enthalpy difference $hj - hi$, then the flow($\dot{m}_{T_{ij}}$) is adjusted by the factor(k_{ij}) and the let down flow is activated. Moreover if the enthalpy(h_j) of the usage header is higher than the enthalpy($h_i - w_{ij}$) of the expanded steam, a steam fraction($k_{ij} - 1$) is by-passed from the following usage header. The same stand for the by-passed steam fraction($r_j - 1$) injected in the let down flow.

2.4 MILP formulation of the cycle energy balance

The energy flow balance for each headers of the superstructure was formulated by[7] as an MILP problem which maximise the overall mechanical work $\sum_{i=1}^{n_v} \sum_{j=i+1}^{n_v} w_{ij}$ transformed in the cycle, n_v beeing the number of steam production headers.
The balance of the usage header j of equation (2) account for the upcoming flows of steam expanded($\dot{m}_{T_{ij}}$) from the producer headers, for the the let-down flow from the previous producer header(L_{j-1}) and for the external water make-up(A_j) and draw-off(S_j).

$$\begin{aligned} & r_{j-1} L_{j-1} + A_j + \sum_{i=1}^{j-1} k_{ij} \dot{m}_{T_{ij}} + \sum_{k=1}^{n_{CO}} \dot{m}_{c_{kj}} = \sum_{i=j+1}^{n_v} \dot{m}_{T_{ij}} + \sum_{k=1}^{n_{CO}} \dot{m}_{h_{jk}} + S_j + L_j \\ & \forall j = 1, \cdots, n_v, \text{ with } k_{ij} = \frac{h_i - h_j - w_{ij}}{h_j - h_{kj}} \text{ and } r_j = 1 + \frac{h_{j-1} - h_{kj}}{h_j - h_{kj}} \end{aligned} \qquad (2)$$

The balance of the condensing header k of equation (3) account for the the flow of cold($\dot{m}_{c_{ki}}$) and hot streams($\dot{m}_{h_{jk}}$) entering, as well as for the external water make-up(A_j) and draw-off(S_j). This balance hold for the n_{CO} condensing headers of the superstructure.

$$\begin{aligned} & A_k + \sum_{j=1}^{n_v} \dot{m}_{h_{jk}} + \sum_{u=k+1}^{n_{CO}} \dot{m}_{c_{uk}} = \sum_{i=1}^{k-1} \dot{m}_{c_{ki}} + S_k + \sum_{i=1}^{nv} \sum_{j=i+1}^{nv} (k_{ij} \dot{m}_{T_{ij}}) + \sum_{j=1}^{n_v - 1} (r_j - 1) L_j \\ & \forall k = 1, \cdots, n_{CO} \end{aligned} \qquad (3)$$

2.5 Validation cases

Three typical steam network configurations from the litterature[5] have been computed. The definitions of the pressures and tempetratrures levels as well as the computed work and relative errors are reported in table 1. The relative error is sensitive to the minimum approach temperature($\Delta T_{min}/2$) for the gas turbine exhaust gases ($25^\circ C$ in Case 1 & 2 and $18^\circ C$ in Case 3).

3 Multi-objective optimization strategy

The solving method decomposes the Mixed Integer Non Linear Problem(MINLP) into two sub-problems (see figure 1): a mixed integer linear programming(MILP) for the integration of the steam network at the lower level and an evolutionary algorithm topying

Case	cycle	Levels				$\dot{W}$	$\dot{Q}$	$\dot{W}$[5] (Err)
		P_i *bar*	T_i °*C*	P_j *bar*	T_j °*C*	*MW*	*MW*	*MW* (%)
Case	Gas turbine	1.04	525	1.04	156	68.0	114.0	
1	$H_{vap,1} \rightarrow H_{use,2}$	37.00	480	0.04	29.0	(36.71)		36.8(0.25)
Case	Gas turbine	1.03	525	1.03	205	68.6	99.4	
2	$H_{vap,1} \rightarrow H_{use2}$	37.00	480	2.90	(131.7)	(2.42)		34.0(2.68)
	$H_{vap1} \rightarrow H_{use3}$	37.00	480	0.04	29.0	(32.49)		
	Gas turbine	1.04	525	1.04	103	69.4	131.3	
Case	$H_{vap,1} \rightarrow H_{use,4}$	60.00	480	0.04	29.0	(35.51)		40.8(2.48)
3	$H_{vap,2} \rightarrow H_{use,3}$	3.30	138	0.02	60.0	(0.51)		
	$H_{vap,2} \rightarrow H_{use,4}$	3.30	138	0.04	29.0	(3.78)		

Table 1: Reference steam cycle[5] (computed value are enclosed in parenthesis).

the values of the steam network configurations together with the power plant operating conditions.

3.1 Non Linear formulation for the steam cycle configurations

The steam network is defined by its n pressure levels P_i (see equation 4), which can be the level of a production header at temperature T_i^{prod} (see equation 6) or/and of a usage header at temperature T_i^{user} and vapor fraction x_i^{user} (see equation 5) greater than 0.85%. These thermodynamic states are defined from de values of the decisions variables $(k_1, \cdots, k_n)$, $(v_1, \cdots, v_{n-1})$ both in $[0,1]$ and $(u_2, \cdots, u_n)$ in $[-1,1]$. Furthermore, the integer variables $(i_2, \cdots, i_{n-1})$ are used to determine if a production header($i = 1$), a usage header($i = 2$) or both of them($i = 3$) have to be placed in the structure. The condensing header is placed by default at the lowest pressure level.

$$\begin{aligned} P_0 &= P^{max} \\ P_i &= P_{i-1} - k_i \cdot (P_{i-1} - P^{min}), \qquad i = 1, \cdots, n \end{aligned} \tag{4}$$

$$\begin{aligned} T_i^{user} &= T^{sat}(P_i) + max(0, u_i \cdot (T^{max} - T^{sat}(P_i))), \qquad i = 2, \cdots, n \\ x_i^{user} &= 1 + min(0, u_i \cdot 0.15), \qquad i = 2, \cdots, n \end{aligned} \tag{5}$$

$$\begin{aligned} T_1^{prod} &= T^{sat}(P_1) + v_1 \cdot (T^{max} - T^{sat}(P_1)) \\ T_i^{prod} &= T^{sat}(P_i) + v_i \cdot (T^{max} - T_i^{user}), \qquad i = 2, \cdots, n-1 \end{aligned} \tag{6}$$

An evolutionary algoritm is used to minimize the grass root investment cost ($C_{GR} = 1.43 \cdot C_{BM}$)[9] of the power plant including the steam network while maximising the power output using a multi-objective strategy. The functions used for the investments cost(C_{BM}), operating cost(C_{OP}) and maintenance cost(C_M) are listed in table (2).

The levilezed cost of electricity $(\tau \cdot C_{GR} + C_{OP} + C_M)/W$ in USD/MWh is computed considering an interest rate $i = 10\%$ and a lifetime $n = 30$ year with annual operating time($t_{OP,year}$) of $8000 h/year$.

Equipments	Cost [$USD_{2007}/year$]	
gas turbine	$C_{BM} =$	$\frac{MS_{2007}}{MS_{2006}} \cdot 10^{4.78016+0.32514 \cdot log(\dot{W})+0.03853 \cdot log(\dot{W})^2}$
	$C_{OP} =$	$t_{OP,year} \cdot \dot{Q}_{fuel} \cdot C_{fuel}$
	$C_M =$	$\frac{MS_{2007}}{MS_{2000}} \cdot (20.136 + 8.27 \cdot \frac{\dot{W}}{0.74569987})$[3]
stean turbine	$C_{BM} =$	$\frac{MS_{2007}}{MS_{2002}} \cdot 10^{1.93778+1.45483 \cdot log(\dot{W})-0.08838 \cdot log(\dot{W})^2}$
	C_{OP}	-
	$C_M =$	$\frac{MS_{2007}}{MS_{2002}} \cdot t_{OP,year} \cdot \dot{W} \cdot 0.004$
heat exchanger	$C_{BM} =$	$\frac{MS_{2007}}{MS_{2006}} \cdot 7038 \cdot N \cdot (\frac{Area}{N})^{0.7948}$[1]
	C_{OP}	-
	$C_M =$	$C_{BM} \cdot 0.05$

Table 2: Investment, operation and maintenance cost functions.

3.2 Conventional NGCC plant

The methodology presented in (§3) has been applied starting with the assumptions of Case 3 (table 1). The results, reported in figure (3) and (4), shows that a steam networks with 3 expansion levels achieves an optimal levelized cost of electicity of 46.5 $\$/MWh$ for an investment cost of 59.2 $M\$_{2007}$ and a power output of 115 MW.

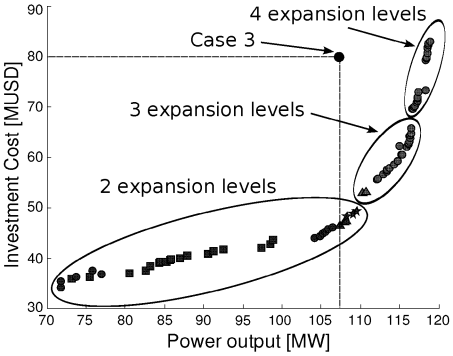

Figure 3: Investment cost/complexity of the steam network (conventional NGCC).

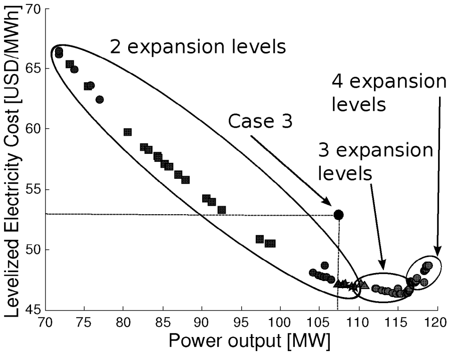

Figure 4: Generating cost of electricity/complexity of the steam network.

4 Conclusion and further work

Based on previous work[7] and methodologies[1], a multi-objective optimization framework that combine evolutionary algorithm and MILP steam network design models has been established to solve the integration of complex steam network for the power plant industry. For a given power plant configuration, it has been shown that the generating cost of electricity exhibits an economic optimum which is function of the degree of complexity of the steam cycle. The need for such method will increase in the future, not only

to design new power plant, but also to propose highly integrated retrofitting solution for the still increasing number of fossil fuel power plant installed in the world that do not incorporate CCS facilities yet
Furthermore, the proposed method could be straightly extended for the design and integration of advanced multi-stages Organic rankine power cycle(ORC) by adding, in the framework, the thermodynamics of the appropriate working fluids or fluid mixtures.

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Nomenclature

CCS	Carbone dioxide capture and storage
NGCC	Natural gas combined cycle

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