PINCH POINT METHOD IN OPTIMIZATION OF ADVANCED COMBINED CYCLES

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ABSTRACT *The pinch point method has been developed to identify energy saving opportunities in industrial processes. The use of the composite curves allows to compute the minimum energy requirement of a process and to determine optimal heat exchange between hot and cold streams. The use of MILP (Mixed Integer Linear Programming) optimization method allows to extend the approach to solve combined heat and power problems. The method is applied here to determine the optimal configuration of combined cycles. It allows to maximize the mechanical power production without having to consider the heat exchangers configuration in the boiler nor in the preheating section. The method is also used to compute the steam extractions or productions and their optimal pressure levels that maximize the mechanical power produced. From these results, the heat exchangers network structure is then determined. Three situations are analyzed : 1) the heat recovery in a classical boiler using air preheating, 2) the gas turbine combined cycle and 3) the " isothermal" gas turbine. The " isothermal" gas turbine is an innovative promising technology that uses a partial oxidation reactor followed by a staged combustion between the expansion stages to reach a quasi isothermal profile during the expansion. This allows to reduce the exergy losses in the gas turbine. The resulting flue gases are used in a combined cycle optimized with the method presented here. Different configurations are discussed. We show that the structure of combined cycles may strongly differ from one to another.*

INTRODUCTION

The pinch point based methods have been developed to identify energy saving opportunities in industrial processes. The pinch point principle has been first suggested by Hohmann [1] in the beginning of the 70ies, the related methods have been largely developed during the 80ies [2]. The basic principle of this method is to use the enthalpy/temperature diagram (figure 1). Such diagrams are built by cumulating the content (quantity) of all the heat sources (hot streams) and of all the heat requirements (cold streams) according to their temperature level (quality). In this diagram, there is a point where the temperature difference between hot streams and cold streams is minimum ; this point is named the pinch point. The value of the smallest acceptable temperature difference (Dtmin) is fixed in order to limit the investment required for the heat exchangers. The identification of the pinch point gives valuable results for the engineers in order to modify the process and optimize the use of energy in the process. It defines the overall energy balance of the system and the area between the hot and the cold composite curves is a measure of the exergy losses. The temperature difference at the pinch point defines the minimum hot utility requirement, the cold utility and the total amount of recoverable heat using countercurrent heat exchange.

One advantage of the method is to represent in a enthalpy/temperature diagram the heat exchange between hot and cold streams in the system (figure 1). The analysis of the shape the such curves allows to identify the possible improvements to be made in the process.

Another interest of the approach is the possibility of solving the pinch point problems by using linear programming algorithms. The research work in the field was pioneered by Cerda et al. [3] and Papoulias and Grossmann [4] These formulations are based on the definition of the heat cascade. After a correction of the temperatures of the hot and cold streams to account for Dtmin contribution of each stream, a heat balance is written for each temperature interval by summing up the heat coming from the hot streams in the interval and the heat coming from the upper temperature intervals and subtracting the heat required by the cold streams in the temperature interval and the heat cascaded to the lower temperature intervals. Of course, the cascaded heat must be equal or greater than zero for all the temperature intervals. This allows to define a set of linear equations that model the ideal heat exchangers network between the hot and the cold streams. The interest of the approach is to allow the computation of the network without having to define the structure of the heat exchangers, i.e. the interconnections between hot and cold streams.

METHODOLOGY

Considering that power plants are composed of hot and cold streams, the idea is to apply a pinch point based method to analyse and optimize the production of electricity. The major difference between industrial processes and power plants is that hot and cold streams are not fixed and that flowrates and temperatures in the system have to be optimized in such a way that the optimal efficiency is reached. The use of linear programming allows to tackle the problem of flowrates optimization, while the problem of temperatures or pressure optimization will be solved by analysis and discretisation. The principle of the approach is to define a process superstructure that includes the possible operations to be analysed and to extract optimal process configurations from the superstructure.

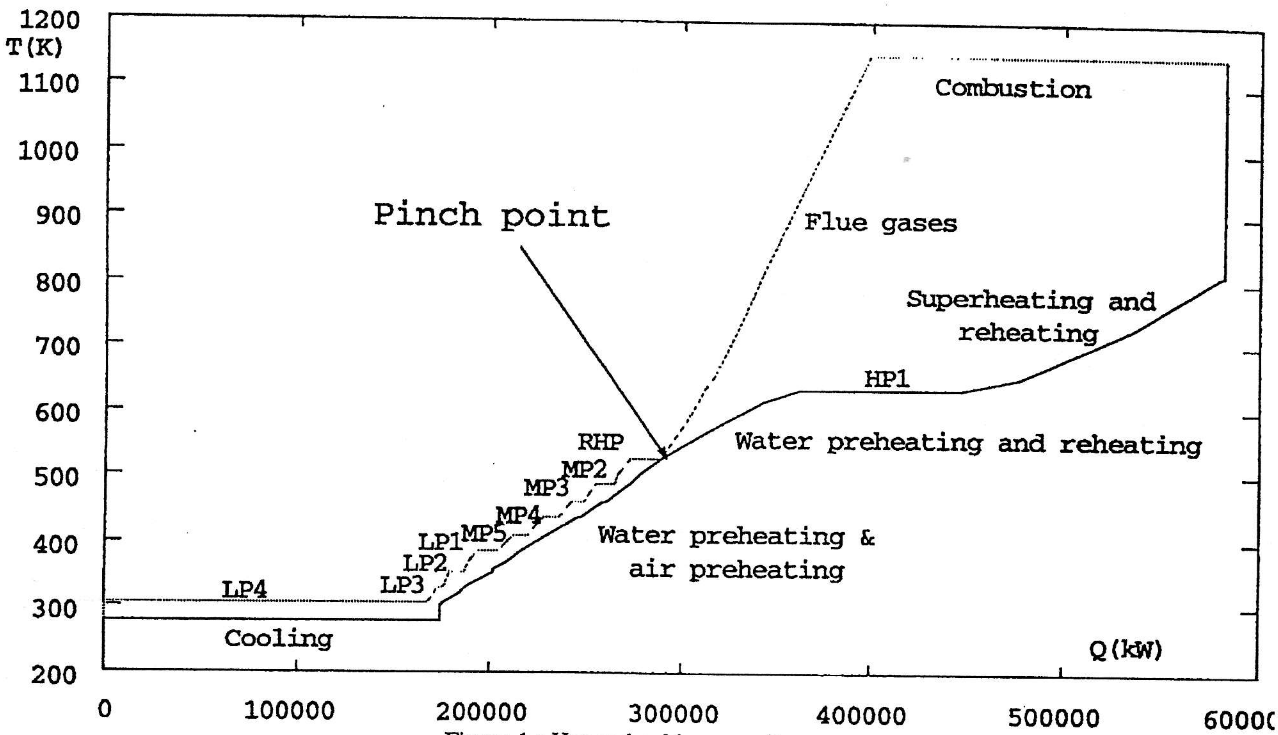

Figure 1 : Hot and cold composite curves

Generate solution using optimization

Using the "Effect Modelling and Optimization" (EMO) approach [7], the power plants and combined cycles are represented by a set of interconnected operations: combustion, air preheating, expansion, steam condensation, steam production, air or water cooling, etc... Each operation defines hot and cold streams (heat effects) whose inlet and outlet temperatures are considered as a characteristic of the operation. Their intensities (flowrates) have to be computed in order to satisfy the mechanical power requirements of the power plant at minimum cost. The interconnections between the operations are of different types considered separately and define the modelling equations. Each heat effect (i.e. energy requirement or production) introduces its own contribution) in the heat cascade defined by the constraints (1.1 to 1.2). Linear equality and inequality constraints are used to define material balances as well as some modelling equations. The process is therefore defined as a superstructure of interconnected operations. A part the necessity of computing the extent of usage of each operation, one has also to compute whether an operation is useful or not. The selection of the operation w is defined by an integer variable y_w and the constraints (1.4). The extent of usage of the operation w is computed by the multiplication factor f_w that multiplies all the effects associated with the operation w. The constraints (1.3) are introduced to impose the overall heat balance of the process. The cost effect appears in the objective function with a proportional term $C2_w$ linked to f_w and a fixed cost $C1_w$ linked to y_w.

$$\sum_{i=1}^{n_w} (f_w\ q_{wk}) + R_{k+1} + R_k = 0 \qquad \forall\ k=1,....,n_i \qquad (1.1)$$

$$R_k \geq 0 \qquad \forall\ k=1,....,n_i+1 \qquad (1.2)$$

$$R_1 = 0,\ R_{ni+1} = 0 \qquad (1.3)$$

$$fmin_w\ y_w \leq f_w \leq fmax_w\ y_w \qquad \forall\ w=1,...,n_w \qquad (1.4)$$

$$y_w\ \varepsilon\ \{0,1\}$$

With
- n_i the number of temperature intervals;
- n_w the number of alternative operations;
- R_k the heat cascaded from the temperature interval k to the lower one;
- f_w the multiplication factor of the effects linked with the operation w;
- q_{wk} the heat load of the thermal effects of the operation w in the temperature interval k. $q_{wk} > 0$ for a hot stream and < 0 for a cold stream;
- y_w the integer variable linked with the use of the operation w. $y_w = 1$ if it is used, $y_w = 0$ if not;
- $fmin_w$, $fmax_w$ respectively the minimum and maximum values accepted for f_w if $y_w=1$.

A subset of linear equations (2.1 - 2.2) is added to model the links between the different operations, i.e. the steam extraction, steam superheating,... These equations are written in such a way that heat balances are verified with respect to the thermal effects defined. The detailed formulation used to model the steam/water cycle is given in Marechal F. [5].

$$\sum_{w=1}^{n_w} (a_{iw}\ f_w + c_{iw}\ y_w) + \sum_{r=1}^{n_r} d_{ir} x_r = b_i\ \forall\ i=1,...,n_e \qquad (2.1)$$

$$\sum_{w=1}^{n_w} (a_{jw}\, f_w + c_{jw}\, y_w) + \sum_{r=1}^{n_r} d_{jr}\, x_r \geq b_j \qquad \forall\, j=1,\dots,n_{ie} \qquad (2.2)$$

$$xmin_r \leq x_r \leq xmax_r \qquad \forall\, r=1,\dots,n_r \qquad (2.3)$$

with n_e the number of effects modelling equality constraints;
n_{ie} the number of effects modelling inequality constraints;
n_r the number of additional linear variables;
x_r the additional variable r used to model the effects of the operation;
a_{iw}, c_{iw} respectively the coefficients of the flowrates and the integer variables of operation w in the constraint i in the effect models. (j refers to inequality constraints);
d_{ir}, b_i respectively the coefficients of the additional variables and the independent term in the constraint i in the effect models;
x_r the additional variables used to model the effects of the operation;
$xmin_r$, $xmax_r$ respectively the minimum and maximum bounds of x_r.

In addition to the heat effects, one has to consider the effects of mechanical power consumption and production. This is computed by adding a mechanical power balance (3). The cost contribution of export (C_{el}) being added to the objective function.

$$\sum_{w=1}^{n_w} f_w\, w_w - w_{el} = 0 \qquad (3)$$

with w_w the mechanical power produced by the operation w calculated for a reference flowrate: $w_w < 0$ for a consumption and > 0 for a production;
w_{el} the production of electricity.

APPLICATION

Let us illustrate the use of the approach to analyse classical power plants and combined cycles. Table 1 gives the only necessary data used to define the water cycle and the combustion in the model. The temperatures are those measured on an existing classical power plant using coal. In the power plant superstructure, all the possible expansions are considered and only the most efficient one will be selected.

Table 1 : data used for the comparison

Fuel	Gas	Coal	
LHV	49589	25450	kJ/kg
Air requirement (fs)	16.97	7.23	kg air/kg
Adiabatic temperature	2329	2111	K

LHV: Lower Heating Value
Cooling system at 288K

Steam levels	Name	P(bar)	T(K)	x*
High pressure steam	HP1	180.0	813	1
First expansion level	RHP	42.0	615	1
Reheating level	MP1	42.0	813	1
Medium pressure draw-off	MP2	22.4	731	1
	MP3	12.6	654	1
	MP4	7.3	584	1
	MP5	3.1	501	1
Low pressure draw off	LP1	1.5	437	1
	LP2	0.54	357	1
	LP3	0.17	330	0.98
Condensate level	LP4	0.05	306	0.96
Deaerating drum	MP5C	6.6	435	0
	LPC	0.04	302	0

*x is the vapour fraction

Classical power plant

The composite curves of the classical power plant used as reference are given on figure 1. The ICC (Integrated Composite Curves) [6] of the water cycle (figure 2) is a more convenient way for the visualisation of the water cycle integration. In this figure the composite of all the hot and cold streams of the water cycle is matched to the composite curve of the hot and cold streams of the fumes and air preheating system. The mechanical power produced is represented by the balance between the hot and the cold streams of the water cycle. On the figure, we have represented the expansion from HP1 to RHP, from MP1 to the condensing levels (LP4) and the mechanical power produced by expanding from MP1 each of the steam extraction flowrates.

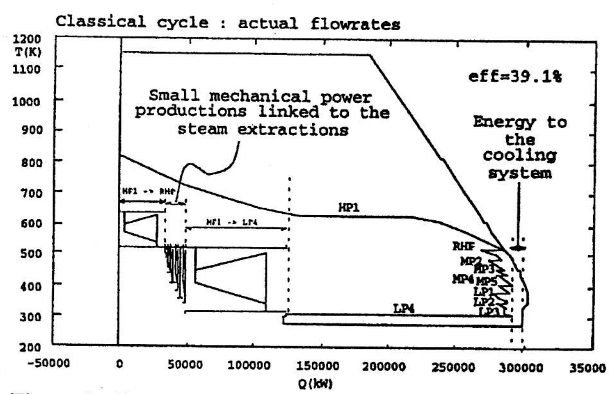

Figure 2 : Integrated composite curves of the system in the actual situation

On figure 2, one can observe that only one pinch point is activated. It corresponds to the steam extraction RHP. The fact that no other pinch point is created indicates that the other steam extractions should be increased in order to reach the fixed DTmin in the exchangers. This value is defined as a technological constraint defining the minimum temperature difference accepted in a heat exchanger. The value is DTmin=2°C for the exchangers in the water cycle, 26°C for the exchangers between the flue gases and the water cycle, 50°C for the exchangers between air and flue gases and 26°C for exchangers between steam and air. The small value of DTmin in the water cycle is explained by the fact that heat recovery by injection (DTmin=0) is possible. In the optimal situation, each extraction flowrate should be maximised in such a way that it creates a pinch point. When pinch points are not created, the energy potential (i.e. the exergy) is not well exploited. At the system level, this means that part of the energy of the fumes is directly sent to the cooling system without producing mechanical power.

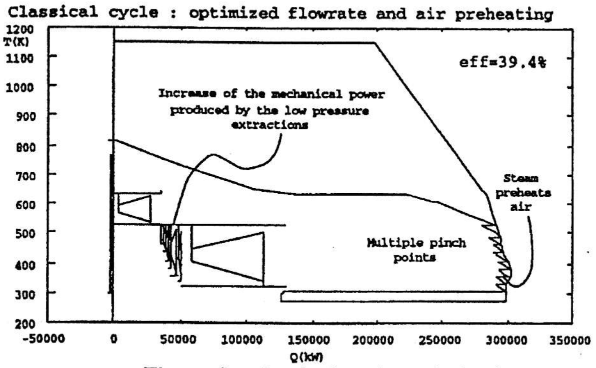

Figure 3 : classical cycle optimized

The ICC of the optimized situation are given on figure 3. We can observe that each steam extraction is used at its maximum level. Steam extraction is used to preheat steam and, in the optimal situation, to preheat air. In the optimal situation, we have considered air preheating up to the temperature of the first extraction (615-25 = 590 K) to account for the effect of heat pumping of the air preheating. Using effect modelling, air preheating is computed in the following way. When considering the combustion, one can consider that the LHV can be divided into two parts: Qr in the radiation zone (above 1173 K) and Qc in the convection zone from 1173 to 298K. The heat available in the radiation zone is constitued by the heat of reaction (QR) and the energy required to preheat fuel (Qf) and the air of combustion (Qa) from the ambient conditions (298K) to 1173 K. When air (and/or fuel) is preheated, the heat for air preheating is smaller and therefore the heat available in the radiation zone is increased. Air preheating should be performed using heat that is not useful to produce high pressure steam, otherwize, the heat required for air preheating is not useful for producing steam (in reality, the heat of preheating is recovered and the balance is zero). If we consider the first extraction of steam, the heat of condensation may be used to preheat air and therefore to increase the production of high pressure steam (above the first pinch point), the balance is an extra amount of mechanical power production in the expansion. In reality, air preheating might be performed by using steam or by using flue gases; if it is the first solution then the exchange between flue gases and water preheating is increased, in the second case, the extra steam extraction is used to preheat water. This is an advantage of the approach, the heat exchanger network is determined afterwards, but we are sure that there exists at least one process configuration with at least the fixed DTmin in all the exchangers. Table 2 gives the results of different alternatives. BASE refers to the actual situation with air preheating to 436 K. OPT refers to the optimized steam cycle and a combustion without air preheating, OPTR refers to the situation with optimal air preheating and steam cycle. Column eff refers to the overall efficiency, HP is the high pressure expansion, MP is the expansion from the reheating level (MP1) to the condensation level and Ext refers to the mechanical power production related to the extractions.

Table 2: results of the comparison of the classical cycles

Case	eff	HP	MP	Ext
BASE	39,1%	27,59%	61,07%	11,34%
OPT	38.6%	26,57%	65,58%	7,86%
OPTR	39,4%	27,77%	61,75%	10,48%

Combined cycles

Combined cycles are composed of a gas turbine and a water cycle to recover the heat at the outlet of the turbine. Two effects are considered to model the gas turbine: the fuel and the air. The link between the two effects is the heat balance of the burner as shown on figure 4, the heat of the fuel has to be used to satisfy the energy requirement of the air at the outlet of the burner. This is the well known effect of dilution to reach the limit temperature at the inlet of the turbine. The data given on figure 4 have been computed using a simulation model for a gas turbine working at 10 bar. The fuel effects relate to 1 kg of natural gas, the air effects relate to one kmol of air. The efficiency is 34 %. If we want to represent a standard configuration of a gas turbine, we will define the air preheating demand at 1373 K and the only possible way of satisfying the heat is by the combustion. On the other hand if we accept to optimize the gas turbine operation, we will define the air preheating as a cold stream to be heated from the outlet of the compressor to the inlet of the turbine introducing in the supestructure the possibility of using a regenerative heat exchange. In both cases, the optimal air flowrate will be computed.

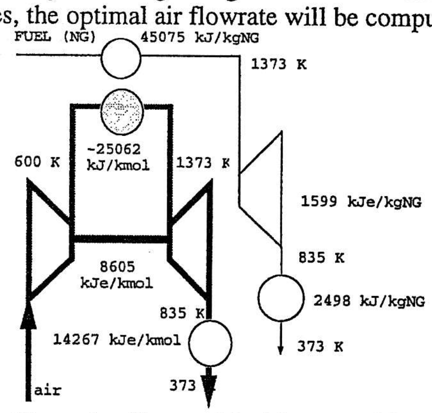

Figure 4 : effect model of the gas turbine

The list of steam levels has been considered as being the one used in the classical cycle analysis. An additional level at 71 bar (HP) has been added to be able to represent the new combined cycles installed in Belgium [9]. We have to insist on the fact that both steam production and steam consumption are allowed in the model. Figure 5 left gives the ICC of the water cycle corresponding to the classical gas turbine optimisation. One can observe that the MP1 level is chosen as the highest pressure level. Steam is produced at different pressure levels in order to recover the energy of the flue gases. Furthermore, steam extractions from the turbine at the levels LP1 and LP2 are used below the stack temperature to preheat the water in the cycle. Figure 5 right gives the ICC of the steam cycle where only HP and MP4 levels have been allowed. In this case, the efficiency is lower, the steam flowrates are optimized and the MP4 level is used to valorize the excess of energy available in the fumes due to the air excess. When steam may be injected in the gas turbine, the steam production for the gas turbine is preferred to the MP4 level production. This is not the case when the multistage steam production is allowed. In the optimal situation, multipressure levels are used in the boiler. The use of integer variables in (1.4) allows to limit the number of levels by imposing a minimum flowrate for each new production level added. This will allow to avoid the generation of solutions with very small flowrates. In this case, the use of integer cuts [7] allows to generate multiple process configurations and therefore obtain automatically the differential benefit of adding or not a pressure level.

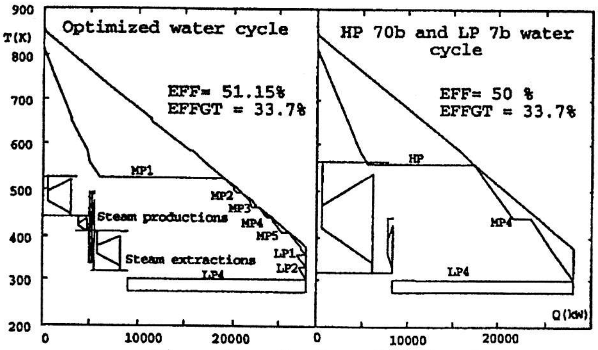

Figure 5: optimal combined cycle

The curves of figure 6 result from the optimization where a regenerative exchange between fumes and air is allowed. In this case, the air flowrate is optimized and we should note that the temperature at the outlet of the compressor creates a pinch point. Above this point, steam superheating and regenerative heat exchange take place. When a regenerative heat exchange is used the air excess is increased and therefore the steam cycle has to be adapted. With respect to the optimal situation, the production of steam at the different pressure levels is more staged and the steam extraction is not used since enough heat remains available in the fumes below the temperature of MP5 to preheat the water of the steam cycle.

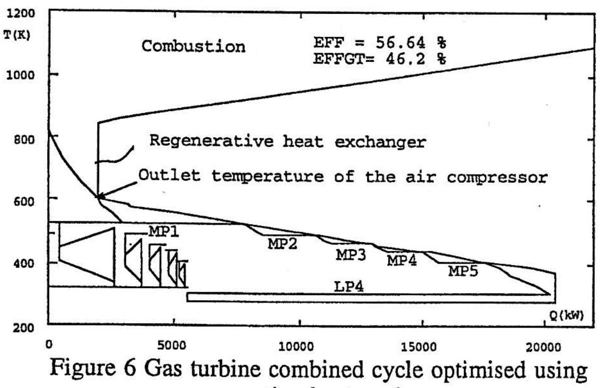

Figure 6 Gas turbine combined cycle optimised using regenerative heat exchanger

Table 3: results for the classical combined cycles

	EFF	GT	Steam
GTEST	49,98%	33,7%	33,83%
GTOPT	51,16%	33,7%	35,35%
GTROPT	56,65%	46,2%	19,15%

Table 3 gives the comparison of the three alternatives studied here above. EFF is the global efficiency of the electricity production, GT is the efficiency of the gas turbine and Steam is the proportion of electricity produced by the steam cycle.

Advanced combined cycles

The isothermal turbine (figure 7) is an innovative promising technology [10] that uses a partial oxidation reactor followed by a staged combustion between the expansion stages to reach a quasi isothermal profile during the expansion. The resulting flue gases have low air excess and therefore will produce lower losses at the stack. The staged combustion allows to reduce the exergy losses all along the gas turbine.

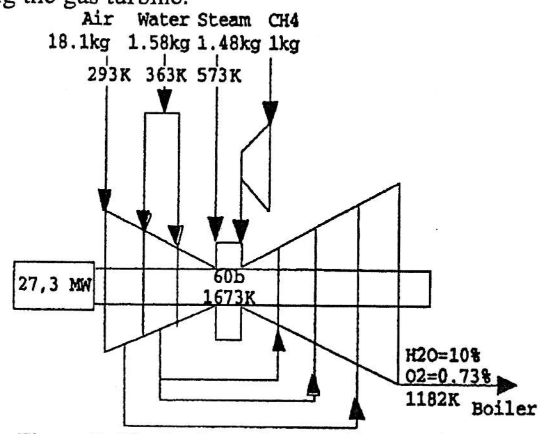

Figure 7: The isothermal gas turbine configuration

The use of the method presented here allows to optimize the steam cycle and the steam production to be integrated to the flue gases of the turbine. This approach is of prime importance since the efficiency of the gas turbine and the flue gases composition will vary according to the steam injection in the reactor. The steam injection is required to a given extent to avoid the formation of coke in the catalytic reactor. The efficiency of the gas turbine increases from 46.5% to 58.9% when the ratio steam/CH4 varies from 0.4 to 3. These values have been computed for a maximum pressure of 60 bar and a turbine inlet temperature of 1673K. Those values are the one proposed by the Gas Research Institute to compare the gas turbines technologies. Due to the reactions limited by an equilibrium, it becomes very difficult to represent the optimization of the turbine using the linear equations used in the EMO model. For this reason, we have used the EMO only to compute the optimal steam cycle to be matched to the flue gases of the turbine. The flowrate, the composition and the temperature of the flue gases as well as the mechanical power production have been computed using the modelling tool VALI II [11] that allows a rigorous computation of the reactions. As steam is injected in the gas turbine, it has to be produced by heat exchange that will be added in the list of cold streams. Table 7 gives the comparison of the different steam injections considered. The steam cycle is identical to the one used in the previous examples. The only difference is that we have added a steam level corresponding to the steam requirement of the gas turbine. Steam/CH4 is the molar ratio of steam versus methane, ToT is the temperature at the outlet of the isothermal turbine, Eff is the overall efficiency of the electricity production, GT is the efficiency of the gas turbine and Steam is the proportion of the mechanical power produced by the steam cycle.

Table 7: efficiencies of the advanced combined cycle.

Steam/CH4	ToT(K)	Eff	GT	Steam
0.43	1153	62,42%	46,56%	25,41%
0.87	1085	62,67%	48,69%	22,31%
1.32	1021	62,69%	50,84%	18,90%
3.09	813	62,05%	58,87%	5,12%

Figure 8 gives the ICC of the steam cycle for two different steam injection flowrates in the reactor. The steam flowrates are computed in such a way that the exergy losses are minimum. This is indicated on the figure by the fact that both curves fit very well together. One can observe that steam extraction is used to produce the hot water injected in the gas turbine. In the first case, steam injection is produced by expansion of HP steam. In the last case, because of the flue gases temperature decrease the injection steam is directely produced without power production. The preliminary results presented here reveal the potentials of the isothermal gas turbine. A lot of degrees of freedom such as temperatures, pressure levels, reactions extent and Dtmin remain to be exploited to define the optimal efficiency that could be reached by this new technology.

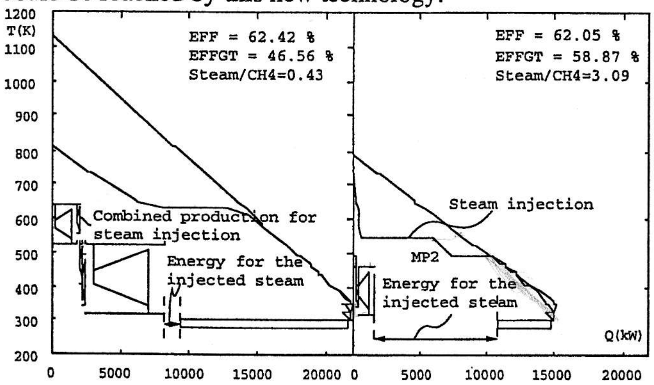

Figure 8: ICC of combined cycles using isothermal gas turbine

CONCLUSIONS

The application of a pinch point based method using MILP optimization has been applied to analyse the integration of the different elements constituting combined cycles. The identification of the different effects that should be considered in a given technology allows to identify possible process improvements and to understand their implication on the other units of the system. The interest of the approach proposed is the usage of a simple model that allows to represent the ideal heat exchanger network without having to make assumptions concerning the interconnections between the different heat exchangers. Of course once a process configuration has been chosen, the heat exchanger network including the heat exchange between water, steam and flue gases should be designed and all the values should be optimized using a non linear and more rigorous model. The graphical representation proposed to visualise the results of the optimization allows to understand the integration of the different elements in the system and shows the way chosen to maximize the electrical efficiency of the process. Using the proposed approach, we have optimized the production of different types of power plants, from the classical production to the combined cycle using an isothermal gas turbine. We demonstrate the benefits that should be obtained by using the proposed approach in terms of understanding and in terms of efficiency increase. We demonstrate as well that modifying a gas turbine technology requires the adaptation of the water loop of the combined cycle in order to maximize the valorisation of the low temperature heat of the flue gases.

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