Sirte University Scientific Journal (Applied Sciences) *Vol.1 1(2), Dec 2021*

Selection of HRSG Parameters for the Triple-Pressure Combined Cycle Power Plant Based on ant Colony Optimization Algorithm

Muammer Alus[1], Khaled Abdusamad[2], Moammer Hamed[3]
alus31@yahoo.de & maalus@elmergib.edu.ly

[1&3]Department of Mechanical and Industrial Engineering, Faculty of Engineering, Elmergib University, Alkhoms, Libya
[2]Department of Mechanical Engineering and Energies, School of Engineering Sciences, Libyan Academy for Postgraduate Studies, Janzour, Libya

Abstract

A new method for the thermoeconomic optimization of triple-pressure heat recovery steam generators (HRSGs) for combined cycle power plants (CCGT) is proposed in this paper. The new optimization method is based on the ant colony optimization algorithm (ACO) and by applying the global optimization software (MIDCO). The optimal values of the most influencing operating parameters are obtained by maximizing the objective function while satisfying a group of constraints. The proposed method is based on optimization of the following operating parameters: the temperature difference between the gas and steam (pinch point) and the drum pressures in the HRSG. The purpose of the thermoeconomic optimization was increasing of the annual cash flow. The optimized combined cycle was compared with the initial case. The results show that there is a potential for considerable improvement of the plant economy when compared to the initial case, where the overall thermal efficiency increased by 0.54 % and the annual cash flow was increased by1.53M$. In addition, the new method could be suitable for research work of the power plants optimization.

Keywords: *combined cycle; heat recovery steam generator; pinch point; optimization.*

1. Introduction

The HRSG is the nexus between the gas cycle and the steam cycle, therefore any change in its design directly affects the variables such as the power generation, thermal cycle efficiency, global cost, and many variables in the cycle. The thermoeconomic optimization intends to find a compromise between the high thermal efficiency and acceptable cost.

Different approaches can be found in the literature regarding the thermoeconomic optimization to obtain a compromise between thermodynamic improvements and economic parameters in triple-pressure HRSGs.

M. Alus and MV. Petrovic[1] developed a simple procedure for optimizing four more impactful parameters in a heat recovery steam generator (HRSG) of combined cycle power plants (CCGTs). The results showed that the proposed optimization method could be used to find an optimum value for the pinch point (PP); Moreover, the proposed optimization method is successfully applied to increase the annual cash flow and decrease the production costs per unit of electrical output as a result of determining the optimum operating parameters for the combined cycle power plant (CCGTs). Godoy et al.[2] presented a nonlinear mathematical programming model for determining the optimal CCGT plants. The optimal plants, characterized by minimum specific annual cost values, are determined for wide ranges of market conditions, as given by the relative weights of capital investment and operative costs. Ahmadi et al.[3] optimized a gas turbine plant for combined heat and power (CHP) generation based on an evolutionary optimization algorithm. The objective function of that study was introduced as the total cost of the plant in terms of dollar per second, which was defined as the sum of the operating cost, related to the fuel consumption. Behbahani-nia et al.[4] presented exergy and thermoeconomic method, which is applied to find the optimal values of design parameters (the pinch point (PP) and gas-side velocity) for a specific HRSG used in combined cycle power plants. Steam pressure levels in the HRSG were not considered to be within the scope of the analysis. Ahmadi and Dincer [5] have introduced thermodynamic analysis through energy and exergy of a combined cycle power plant with a supplementary firing system by minimizing the objective function (cost, mass flow rate, etc.) using a genetic algorithm type optimization method. Valdes and Rapun[6] presented a method for optimization of HRSG based on the utilization of influence coefficients, which takes advantage of the influence of the design parameters on the cycle thermodynamic performance, although its application to multiple pressure configurations becomes complex because of the need to evaluate a large number of combinations. Rovira et al.[7] present a methodology to achieve thermoeconomic optimizations of CCGT power plants taking into account the frequent off-design operation of the plant. In addition, the methodology is applied to optimize several CCGT configurations operating under different scenarios of energy production. Franco and Russo[8] used an alternative method to the PP method. Actually, two different objective functions have been utilized: one given by the energy losses due to the heat transfer between fluids and the other represented by a cost-the sum of the cost of the HRSG and the cost of the exergy losses. The obtained results of the proposed approach show that reaching overall CCGT efficiency near 60% is possible. The study did not include economic parameters such as the annual cash flow. Valdes et al. [9] carried out a thermoeconomic optimization model regarding the HRSG of combined cycle gas turbine power plants using a genetic algorithm. They proposed two different objective functions: one minimizes the cost of production per unit of output, and the other maximizes the annual cash flow. The authors adopted the PP of the experience in his study on the selection.

Previous studies prompted us to focus on thermoeconomic optimization by appling a new optimization method based on ant colony optimization algorithm and which was applying global optimization software (MIDCO). In order to evaluate the proposed approach, the results obtained from applying the new method in the thermoeconomic optimization are compared with the initial case.

2. Ant Colony Optimization algorithm

In the present paper, an attempt was made to develop a method to improve the economic performance parameters of triple-pressure HRSG for combined cycle power plants using an optimization algorithm based on the ant colony optimization (ACO). The ACO is a probabilistic technique for solving computational problems, which can be reduced to finding good paths through graphs. To find food, biological ants start to explore the area around their nest randomly at first. If an ant succeeds in finding a food source, it will return back to the nest, laying down a chemical pheromone trail marking its path. This trail will attract other ants to follow it in the hope of finding food again. Over time the pheromones will start to evaporate and therefore reduce the attraction of the path, so only paths that are updated frequently with new pheromones remain attractive. Short paths from the nest to a food source imply short marching times for the ants, so those paths are updated with pheromones more often than long ones. Consequently, the shorter paths with ongoing time will attract more and more ants. As a final result, a very short path will be discovered by the ant colony [10&11].

To solve the optimization problems of HRSG in an efficient and robust way, an optimization algorithm and software, based on an extension of the Ant Colony optimization metaheuristic is applied. These novel extensions for the well-known Ant Colony Optimization (ACO) framework are introduced by Schlueter et al.[10&11], which allow the solution of Mixed Integer Nonlinear Programs (MINLP) and multi-objective optimization.

3. Optimization strategy

The gas turbine, as a part of a CCGT is not subject to optimization due to many manufacturers of gas turbines offer several models in every power range. Therefore, any changes in parameters or size would request large additional development and cost. Further, the steam production at the individual pressure levels depends on the selected value of pressure and the selected value for PP. Consequently, the electrical output of the steam turbine plant w_{ST} and the thermal efficiency η_{CCGT} of the whole CCGT, are affected by the selection of these parameters.

The methodology, which used in this work, optimize PP and the other operating parameters (drum pressures) in the same time delivering the maximal annual cash flow (B). Furthermore, an efficient optimization strategy based on ant colony algorithm was applied to find the optimal set of parameters, which delivers the maximum annual cash flow of the plant. Figure 1 displays the flow chart of the optimization

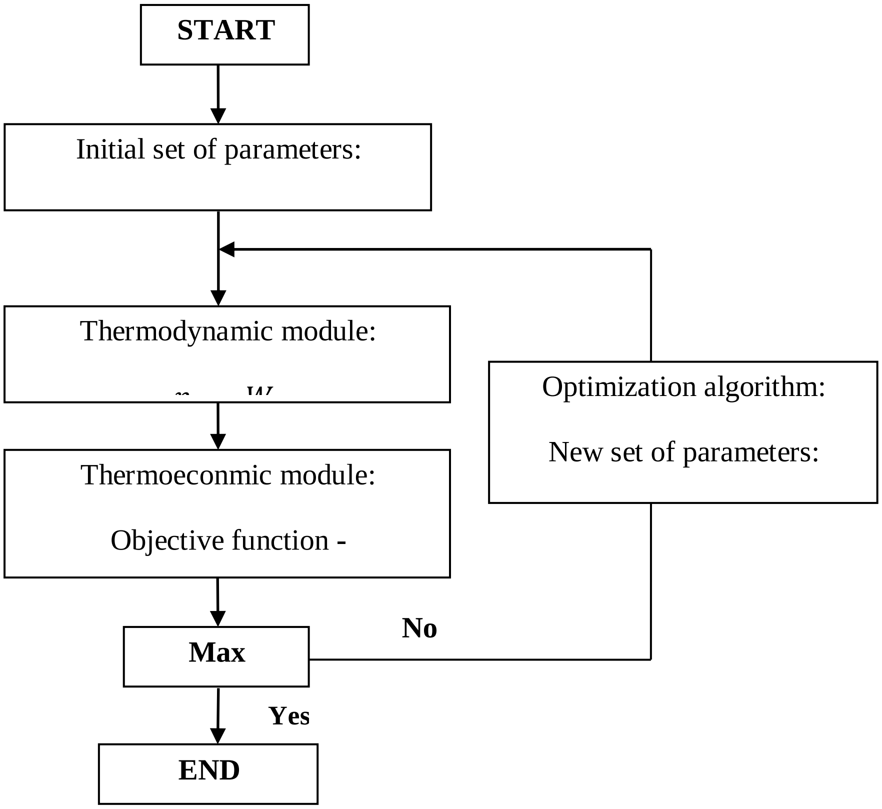

Figure 1. *The flow chart of the optimization strategy for a three-pressure CCGT.*

4. Thermodynamic module

4.1. Description of the Module

A CCGT cycle with a triple-pressure HRSG was considered in this research as an example. The same procedure can be applied for single-pressure or double-pressure CCGT. Figure 2 shows a schematic diagram of the triple-pressure HRSG of a combined cycle power plant. Figure 3 shows the temperature-transferred diagram for the combined cycle power plant (CCGT), which corresponding to Figure 2. The diagram shows important optimization parameters that are three pinch points (PP) in all of the three pressure HRSG levels (HP, IP and LP level) where the temperature difference for heat transfer is expected to be a minimum. The red line (GT) in Figure 3 illustrates the cooling of the exhaust gas from inlet to outlet in the HRSG. The other lines (HP, IP and LP) illustrate the water/steam heating process at high-pressure, intermediate-pressure and low-pressure level.

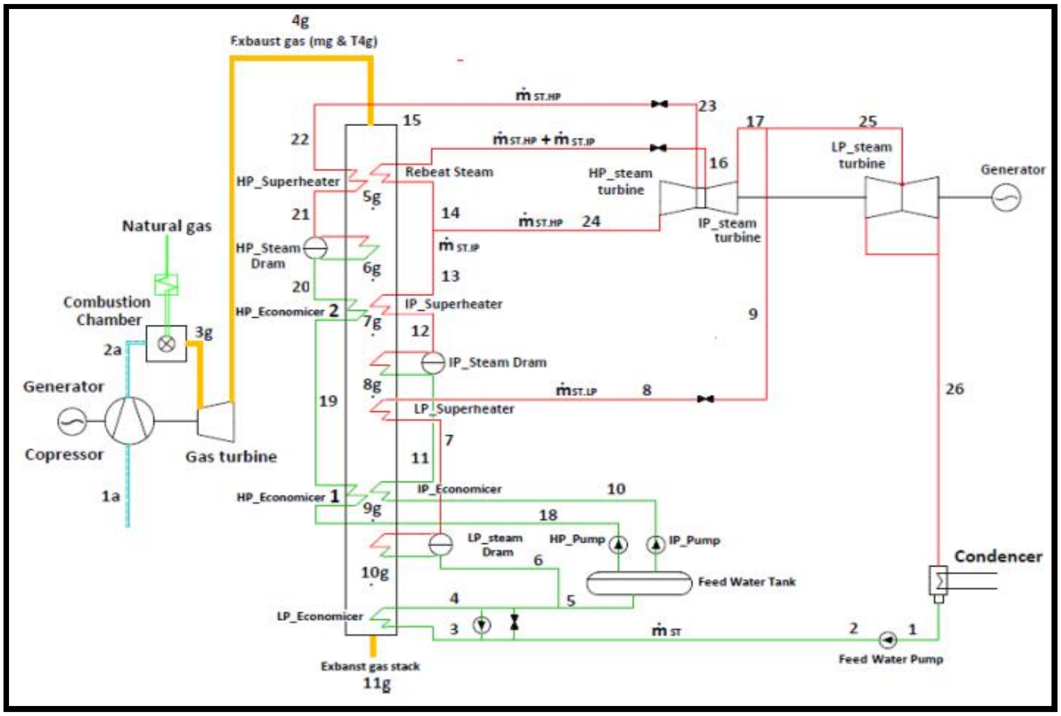

Figure 2. A schematic diagram of the triple-pressure HRSG of a combined cycle power plant

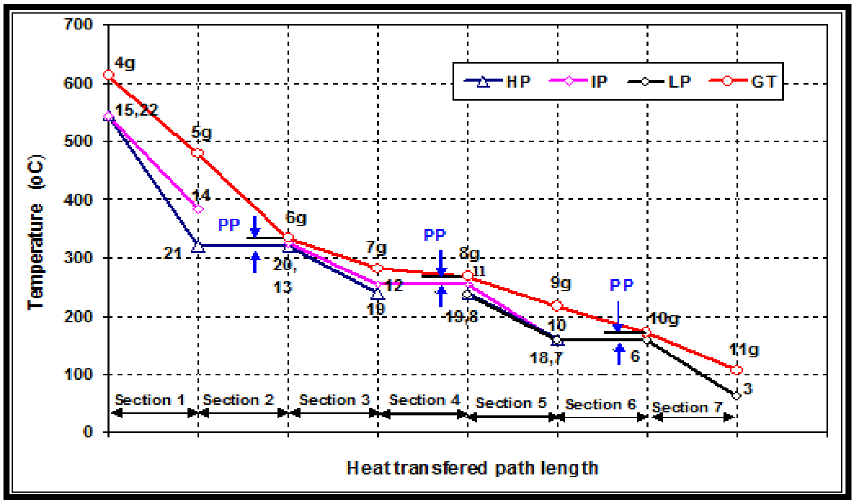

Figure 3. Temperature-transferred heat diagram for triple-pressure HRSG of CCGT

The data of the selected gas turbine and the assumed parameters for CCGT cycle for the initial case are according to the literature[1,2,6,12] , and presented in Table 1.

Table 1: Gas turbine parameters and assumptions for component performances of the CCGT with the triple-pressure HRSG selected for the optimization[1,2,6,12]

Parameter	Value
1. Gas Turbine Cycle	
Electrical power at the generator output [MW]	278
Exhaust gas mass flow [kg/s]	670.8
Exhaust gas temperature at the gas turbine outlet [ºC]	582
The gas turbine efficiency [%]	39.1
Lower heat value of the fuel [kJ/kg]	47,141
2. Steam turbine cycle	
Live steam temperature at the inlet of the HP steam turbine [ºC]	545
Live steam pressure (HP) (bar)	104
Temperature of the reheat steam (IP steam turbine) [ºC]	545
Pressure of reheat steam (IP) (bar)	36
Pressure of the inlet LP steam turbine (LP) (bar)	5
The pinch point temperature difference for HP, IP and LP [ºC]	13
Feed water temperature [ºC]	60
Low-pressure steam turbine outlet (condenser pressure) [bar]	0.057

4.2. Constrains:

Each optimization problem needs some reasonable number of constraints defined due to the physical limitations. In this particular optimization study, a list of constraints selected are given in Table 2. The search domain is defined between these constraints by optimization software for thermo-economic optimization. As a result, each optimized operating parameter lies within this range.

Table 2. List of constraints for optimization.

Constraints	Reason
$5^{o}C < PP < 20^{o}C$	Second law of thermodynamic limitation
2 bar < LP < 6 bar	Commercial availability
20 bar < IP < 50 bar	Commercial availability
100 bar< HP < 200 bar	Commercial availability
$T_{11g} \geq 93\ {}^{o}C$	To avoid formation of sulfuric acid in exhaust gases

4.3. Thermodynamic Module Calculation

The first step of a thermoeconomic optimization is a thermodynamic analysis. It is performed to calculate thermodynamic parameters (the thermal efficiency of the plant and the steam turbine gross power), which will be used to find fuel costs, the details of the components (the surface area of the HRSG, for example) and the investments costs.

In this work values for PP in all of the three pressure HRSG parts are considered as equal as shwon in figure 3. The assumptions and calculations that used in calculating the mass and energy balance, and also the thermodynamic parameters were made according to the reference M. Alus and MV. Petrovic[1]. The results calculations of the thermodynamic parameters for the initial case are presented in Table 3.

Table 3. Initial case – Results of the thermodynamic parameters.

Parameter	Value
Steam turbine cycle:	
Steam turbine gross power [MW]	132.24
Steam mass flow [kg/s]	102
• High-pressure steam mass flow ($\dot{m}_{ST,HP}$) [kg/s]	78
• Intermediate-pressure mass flow ($\dot{m}_{ST,IP}$) [kg/s]	8
• Low-pressure mass flow ($\dot{m}_{ST,LP}$) [kg/s]	16
Combined cycle power plant:	
Total electrical power of CCGT [MW]	410.24
CCGT plant thermal efficiency [%]	57.7

5. Thermoeconmic module - Determination of the economic parameters

To perform the optimization, some economic parameters should be assumed, relations between the thermodynamic parameters and capital cost have to be established and objective function calculated.

The thermoeconomic optimization was performed under the following conditions, which were selected according to experience and the current market conditions:

i. The average life of the combined cycle power plant is 20 years,
ii. The power plant is operated for 7500 h/year,
iii. The interest rate 10%,
iv. The unit selling price of generated electricity is 0.114$/kWh,
v. The price of natural gas is 0.0467 $/kWh,

vi. The investment costs of the economizer, evaporator, superheater and reheat sections of the HRSG are 45.7, 34.8, 96.2 and 56.2$/m2, respectively [6].

5.1 Capital cost functions of components

In energy systems, determination of the capital costs is one of the main problem in the analysis of the economic effectiveness of investments. The best way to find the overall capital cost of the plant is to establish the function between the cost and characteristics (capacity, parameters and performances) of individual components. The cost functions for the major components of a combined cycle power plant that were applied in the scope of this work are presented in Table 4.

The cost functions provide the net capital costs of the components, excluding transport and assembly costs, supervising, accessories, engineering and project management, commissioning and other connected costs. These additional costs can be calculated by multiplying the net cost C by an additional cost factor R.

The total capital costs (investment costs) of a combined cycle power plant may be expressed as

$$C_{CCGT} = R.\left(C_{GT} + C_{HRSG} + C_{ST} + C_{Cond} + C_{Pump} + C_{Gen.}\right) \qquad (1)$$

In this calculation, the value of R is assumed to be 3. According to a careful analysis of the market conditions and the authors' own experiences, the cost functions for the components and the value of the additional cost factors are selected.

Table 4. Functions of the device costs

Component	Function
HRSG [5]	$C_{HRSG} = 2.31\left(\sum_{E} k_E A_E + \sum_{V} k_V A_V + \sum_{SH} k_{SH} A_{SH} + \sum_{RE} k_{RE} A_{RE}\right)$
Steam turbine [13]	$C_{ST} = 6000.\, W_{ST}^{0.7}$
Stainless-steel condenser [13]	$C_{Cond.} = 280.\ A_{Cond.}^{1.01}$

Pump [13]	$C_{Pump} = 3540.W_{Pump}^{0.71}$
Generator [14]	$C_{Gen.} = 60.W_{Gen}^{0.95}$

5.2 Objective function

The annual cash flow B has been chosen as an objective function of optimization, because the aim of the optimization was to find the most profitable power plant.

The annual cash flow B is the difference between the annual total income I_{tot} and the total cost per year C_{tot} as pointed out by Valdes et al. [15] :

$$B = I_{tot} - C_{tot} \tag{2}$$

The annual total income can be calculated using

$$I_{tot} = S.W_{CCGT} \,.\, \tau \tag{3}$$

where S is the selling price per unit of electricity and τ is the number of operating hours per year.

The total cost per year includes the total annual fuel cost, the amortization cost and the operating and maintenance cost, as shown in the following equation:

$$C_{tot} = C_f + C_a + C_{o\&m} \tag{4}$$

The total annual fuel cost C_f is defined as follows:

$$C_f = c_f \,.\left(\frac{W_{CCGT}}{\eta_{CCGT}}\right)\cdot \tau \tag{5}$$

The amortization cost C_a summarized as pointed out by Valdes et al. [15] :

$$C_a = C_{CCGT} \cdot \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) \tag{6}$$

where n is economic life of the plant and i is the discountrate.

The operating and maintenance cost $C_{o\&m}$ is assumed to be 10% of the total plant cost as pointed out by Valdes et al. [19]:

$$C_{o\&m} = 0.10 \cdot (C_{tot}) \tag{7}$$

6. The results of optimization

The variations of the variables of the HRSG of the combined cycle power plant during the optimization process are shown in Figures 4, 5, 6 and 7. The convergence of the objective function with a number of generation of triple-pressure HRSG is presented in Figure 8.

The objective function, i.e. the maximum annual cash flow (B) as defined by “Eq. (2)” , has achieved maximum of 56.773 M$ (Million dollars) after about 5000 iterations.

It can be seen that for the pinch point and all three pressures (HP, IP and LP steam), which were the subject of optimization, there is an optimal value at which the best results can be achieved. These values are 8.34 ^{o}C for PP and pressures: 157 bar for HP steam, 36.3 bar for IP steam and 3.6 bar for LP steam. The calculated value for the pinch point seems reasonable based on what is suggested by experience.

Comparing the results, it can be observed that the maximum value for HP steam is obtained in the optimized case (157 bar), which is higher than it was in the initial case (104 bar). In addition, the optimum value for IP steam was very close to the initial case. In contrast, the optimization identified a lower value for LP steam than was used in the initial case. The increased costs for HRSG due to increasing the initial costs for the HP-level (area, piping, material, etc) are covered by a larger production of electricity.

Table 5 shows a comparison between the initial case and the thermoeconomic optimization case. The results show that the financial parameters are better than the initial case. Thermoeconomic optimization intends to achieve a trade-off between enhancing the thermal efficiency and maximum annual cash flow *B*.

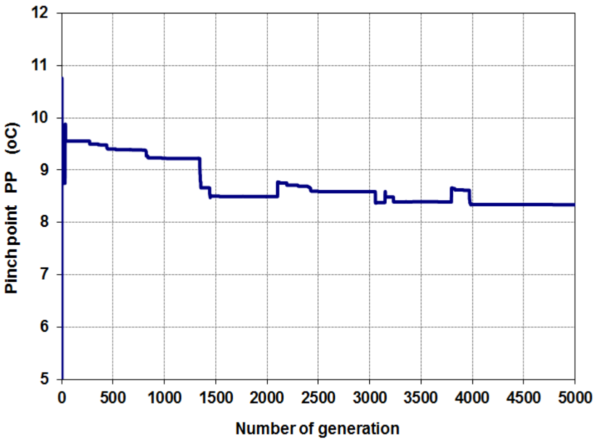

Figure 4. *Optimization history of the pinch point*

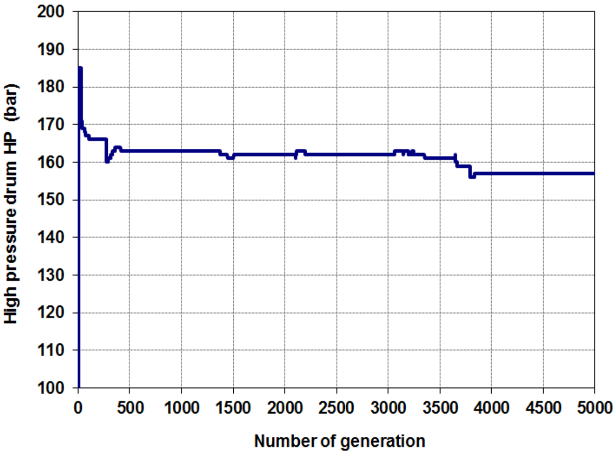

Figure 5. *Optimization history of the high pressure steam (HP)*

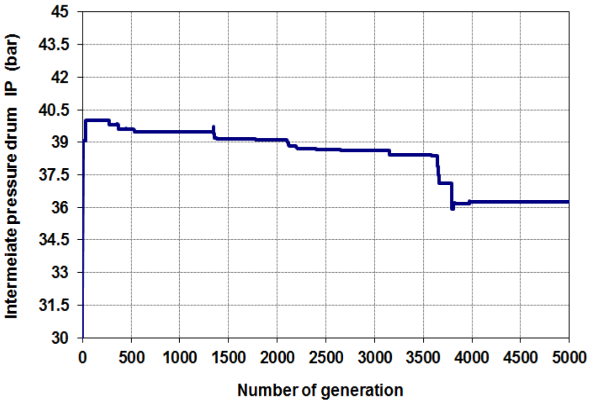

Figure 6. Optimization history of the intermediate pressure steam (IP)

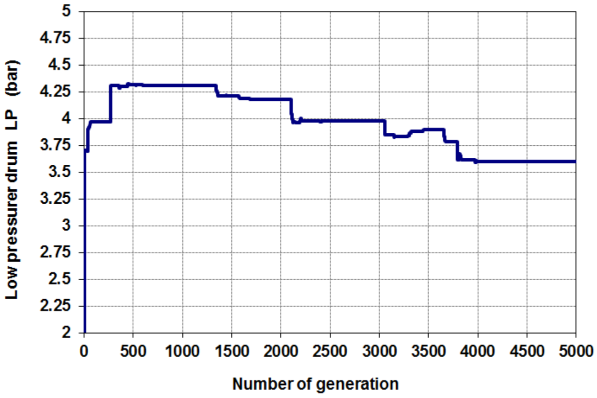

Figure 7. *Optimization history of the low pressure steam (LP)*

In our case, applying the developed method, the thermal efficiency and electrical output of the selected combined cycle were increased. On the other hand, the annual cash flow *B* was increased.

It means that it is possible to improve the economy of the triple-pressure HRSG power plant and that the thermoeconomic method presented here has been successfully applied.

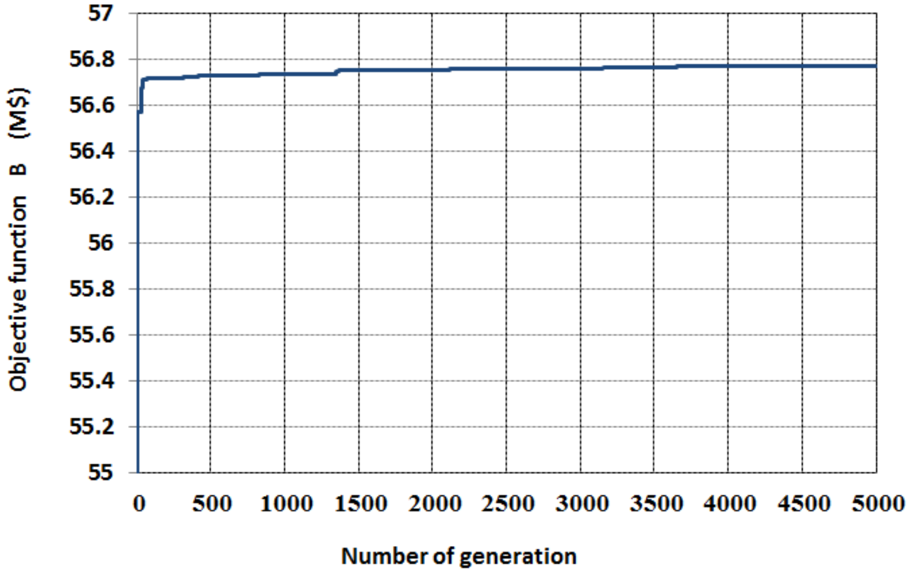

Figure 8. *The convergence of the objective function with number of generation of triple-pressure HRSG.*

Table 9. Comparison between the initial case and the thermoeconomic optimization case

Parameter	Initial case	Thermoeconomic optimized case
Pinch point [°C]	13	8.34
High pressure drum [bar]	104	157
Intermediate pressure drum [bar]	35	36.27
Low pressure drum [bar]	5	3.6
Combined cycle efficiency [%]	57.70	58.24
Combined cycle-gross power [MW]	410.24	414.10
Production cost [c$/kWh]	9.604	9.572
Annual cash flow [M$/year]	55.246	56.773

7.Conclusions

In this paper, Thermoeconomic optimization method had been developed to improve the performances of triple-pressure combined cycle power plants. A methodology of selection of steam pressures (HP, IP and LP) and steam mass flow rate of HP, IP and LP levels for a triple pressure CCGT cycle is presented. The thermoeconomic module establishes a connection between the HRSG parameters and the investment costs. Furthermore, an efficient optimization strategy based on the ant colony algorithm was applied to find the optimal set of parameters, which deliver the maximal annual cash flow of the plant.

The developed thermoeconomic method of HRSG parameters optimization was successfully applied to an example of CCGT cycle. It was shown that a significant improvement in the economic parameters is possible. Compared with the initial case, the annual cash flow B was increased by 1.53 M$ (approx. 2.7%), the electrical output by approx. 4 MW and the overall thermal efficiency by 0.54 percent point. Finely, the new method (ACO) by applying the global optimization software (MIDCO) showed satisfactory results compared to the initial case, and gave the possibility of using it in the research work of the power plants optimization.

References

[1]. Alus M. & Petrovic MV. (2012). Optimization of the triple-pressure combined cycle power. *Thermal Science*. 16(3), 901- 914.

[2]. Godoy E., Benz SJ., Scenna NJ. (2011). A strategy for the economic optimization of combined cycle gas turbine power plants by taking advantage of useful thermodynamic relationships. Applied Thermal Engineering. 31(5), 852-871.

[3]. Ahmadi P., Almasi A., Shahriyari M., Dincer I. (2012). Multi-objective optimization of a combined heat and power (CHP) system for heating purpose in a paper mill using evolutionary algorithm. International Journal of Energy Research. 36(1), 46-63.

[4]. Behbahani-nia A., Sayadi S., Soleymani M. (2010). Thermoeconmic optimization of the pinch point and gas-side velocity in heat recovery steam generators. Journal of Power and Energy. 224(6), 761-771.

[5]. Ahmadi P. & Dincer I. (2011). Thermodynamic analysis and thermoeconomic optimization of a dual pressure combined cycle power plant with a supplementary firing unit. Energy Conversion and Management. 52(5), 2296–2308.

[6]. Valdes M. & JL. Rapun JL. (2001). Optimization of heat recovery steam generators for combined cycle gas turbine power plants. Applied Thermal Engineering. 21(11), 1149-1159.

[7]. Rovira A., Sánchez C., Muñoz M., Valdés M., Durán MD. (2011). Thermoeconomic optimization of heat recovery steam generators of combined cycle gas turbine power plants considering off-design operation. Energy Conversion and Management. 52(4), 1840–1849.

[8]. Franco A. & Russo A. (2002). Combined cycle plant efficiency increase based on the optimization of the heat recovery steam generator operating parameters. International Journal of Thermal Sciences. 41(9), 843–859.

[9]. Valdes M., Duran MD., Rovira A. (2003). Thermoeconomic optimization of combined cycle gas turbine power plants using genetic algorithms. Applied Thermal Engineering. 23(17), 2169–2182.

[10]. Schlueter M., Egea JA., Banga JR. (2009). Extended ant colony optimization for non-convex mixed integer nonlinear programming. Computers & Operations Research. 36(7), 2217-2229.

[11]. Schlueter M., Egea JA., Antelo LT., Alonso AA., Banga JR. (2009). An Extended Ant Colony Optimization Algorithm for Integrated Process and Control System Design. Industrial & Engineering Chemistry Research. 48, 6723–6738.

[12]. Sukru B., Recep O., Zehra Y. (2003). Condenser Optimization in Steam Power Plant. Journal of Thermal Science. 12(2), 176-179.

[13]. Silveira JL. & Tuna CE. (2003). Thermoeconomic analysis method for optimization of combined heat and power systems. Progress in energy and Combustion Science. 29(6), 479-485.

[14]. Attala L., Facchini B., Ferrara G. (2001). Thermoeconmic optimization method as design tool in gas-steam combined plant realization. Energy Conversion and Management. 42(18), 2163–2172.

[15]. Valdes M., Rovira A., Durán MD. (2004). Influence of the heat recovery steam generator design parameters on the thermoeconomic performance of combined cycle gas turbine power plants. International Journal of Energy Research. 28,1243–1254.