THERMO-ECONOMIC OPTIMIZATION OF WASTE HEAT RECOVERY SYSTEMS

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The present paper addresses the application of genetic algorithms for economic optimization versus the thermodynamic optimum in an engine combined cycle. For simplification, the model uses only the flue gas chemical composition and mass flow from the gas exhausted by the engine and approaches the bottoming cycle as an independent cycle. The algorithm is based on Pinch Analysis and pressure variation in the heat recovery steam generator.

Keywords: engine combined cycle, heat recovery steam generator, genetic algorithms, optimization and bottoming cycle

1. Introduction

Improvements made in the combined cycle efficiency over the last years made a statement on the energy market, thus most of single cycle power plants were equipped with bottoming cycles, also known as waste heat recovery systems (WHR), consisting of a heat recovery steam generator (HRSG) and a steam turbine. Depending on the type of the combined cycle, power plants achieve typical effective electric efficiencies of up to 90% — a dramatic improvement over the average 33% efficiency of conventional fossil-fuelled power plants.

Other pressing issues are the ability of the power system to respond fast to load alternations and the possibility of running on different fuels. Internal combustion engines (ICE) apply to these conditions, also offering a high electrical efficiency (up to 47%) in stationary operation. The exhaust gases from ICEs, which can be utilised for power generation in a bottoming cycle, have a temperature level of 300 ºC to 400 ºC depending on the engine type, thus making them a reliable hot source for combined cycles.

The objective of this study is to optimize the design of the bottoming cycle from both an economic and a thermodynamic viewpoint. If energy recovery and pollution control go hand in hand for economic and environmental reasons, efficiency is considered to be a conflicting goal. A significant role in the efficiency versus economics controversy is played by steam pressure and pinch and approach points.

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2. Thermodynamic Cycle

In the present work the engine combined cycle considered consists of an internal combustion engine (ICE), a heat recovery steam generator (HRSG) and a steam turbine, which expands the collected steam from the HRSG to the condensing pressure level.

Depending on the availability of cooling water on-site, the steam is condensed by an air or water cooled condenser. In the following calculations a water cooled condenser is assumed which can achieve a pressure level of 0,1 bar [1]. A schematic presentation of this system is shown in Figure 1.
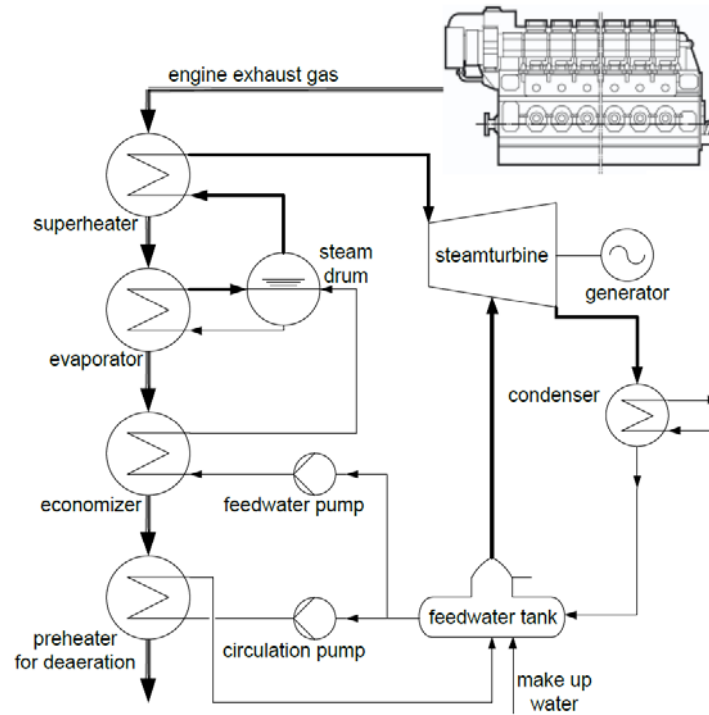

Fig. 1. Schematic presentation of the ICE cycle

The gas exhausted from the ICE is sent into the natural circulation HRSG, considering no variations in temperature or pressure. The HRSG is equipped with only one pressure level consisting of one economizer, one evaporator, one superheater and one preheater for deaeration. The feedwater is heated in an economizer to almost saturation temperature before it enters the drum. A vaporisation loop is formed between the evaporator and the steam drum. The saturated steam enters the superheater which feeds the steam turbine. The residual heat of the flue gases after exiting the economizer section is used in a deaerator

loop where water from the feedwater tank is heated and partly evaporated for the purpose of heating the feedwater tank. For optimization reasons, the pressure is considered as a variable parameter.

In order to determine the thermal regime of the HRSG we apply the economizer pinch/approach methodology [2]. The temperature profiles for gas and water/steam in the HRSG are shown in Figure 2.
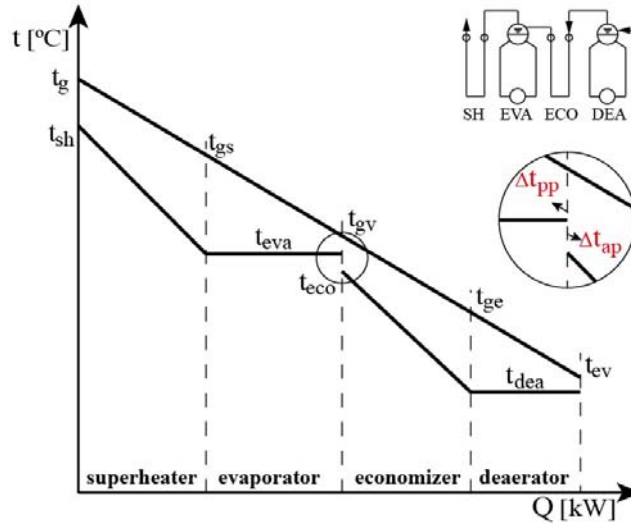

Fig. 2. t-Q diagram for the heat recovery steam generator (HRSG)

Energy recovered in a HRSG is a function of several variables including: gas inlet temperature to HRSG; steam pressure; number of steam pressure levels; pinch and approach points. By having a given gas inlet temperature and only one steam pressure level, the work will focus on the optimization of the remaining parameters: pinch/approach points and steam pressure.

For the case presented herein, the pinch and approach temperature are defined as following:

$$\Delta t_{pp} = t_{gv} - t_{eva} = \text{economizer pinch};$$ (1)

$$\Delta t_{ap} = t_{eva} - t_{eco} = \text{economizer approach};$$ (2)

$$\Delta t_{ap-SH} = t_g - t_{sh} = \text{superheater approach}.$$ (3)

Pinch and approach points determine gas/steam temperature profiles and have a great impact in both thermal and economical optimization. Higher pinch points provide an increased gas temperature when entering the economizer which reduces the heat transfer in the superheater and the evaporator and ultimately resulting in a lower steam generation rate for a cheaper HRSG. Lower pinch points provide higher steam quality because of the high rate of heat transfer in the

superheater and evaporator, but require more material, implicating a costlier HRSG.

The other parameter affecting the HRSG efficiency is the steam pressure. The saturation temperature is proportional to steam pressure thus, the flue gas temperature after leaving the evaporator (t_{gv}) is higher with less steam generation as compared to lower steam pressure case. Higher steam pressure requires higher flue gas temperature.

By applying the thermal and material balance for the superheater and evaporator sections, the energy absorbed by these two heat exchangers is:

$$Q_{SH+EVA} = m_g \cdot C_{pg} \cdot (t_g - t_{gv}) \cdot hl = m_s \cdot (h_{SH} - h_{ECO}) \qquad (4)$$

where: m_g =gas flow, kg/s; C_{pg} =gas specific heat at the average gas temperature, kJ/kg·K; t_g, t_{gv} =gas temperature at various locations, as shown in Fig.2.,°C; hl=heat loss factor, typically 0,99 to 0,995 [3]; m_s =steam flow, kg/s; h_{SH}, h_{ECO} =steam enthalpy at superheater exit and water enthalpy at economizer exit, kJ/kg.

Steam generation is proportional to $(t_g - t_{gv})$. With less steam generated, the water flow through the economizer is lower, and the heat recovery potential is also reduced. By setting an exit temperature for the flue gases (t_{ev}), steam pressure has an economic impact on the HRSG, besides the tube selection and costs.

3. Simulation

In order to develop a cost-effective power plant we resort to artificial intelligence implicating multi-objective optimization.

Thermodynamic cycle simulation was done using the Global Optimization Toolbox from MatlabR2011b and gas properties were calculated with NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) version 9.0. Steam and water properties are based on the International Association for Properties of Water and Steam Industrial Formulation 1997 (IAPWS IF-97) [4] and calculated using the XSteam function.

The first and most important step in the thermal analysis of the WHR system is to define the given parameters. The decision variables are set as unknown elements of a matrix so that they can be used in the thermal balances that define the WHR system.

The steam generation rate in the HRSG is determined by taking a control volume of the superheater and evaporator and by performing the energy balance.

$$m_s = \frac{m_g (c_{p\_tg} \cdot t_g - c_{p\_tgv} \cdot t_{gv})(1 - hl)}{h_{sh} - h_{eco\_out}}, \text{ kg/s} \tag{5}$$

where c_p - the specific heat of gas, h_{sh} and h_{eco_out} are the enthalpies of the steam at the superheater outlet and water at evaporator inlet, respectively. All enthalpies are calculated using the XSteam function, based on the IAPWS IF-97. The specific heat of the exhaust gas is determined using the relation from:

$$c_p = \frac{R}{M}(\alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4), \tag{6}$$

where T is in K, equation valid from 300-1000 K, R is the universal gas constant, M is the molar mass of the gas, and α, γ, δ and ε are the gas constants for various ideal gases.

Thermal heat flow for each heat exchanger is determined by applying the thermal balance equation:

$$Q_{h\_ex} = m_s \cdot (h_{h\_ex\_out} - h_{h\_ex\_in}), \text{ kW} \tag{7}$$

where Q_{h_ex} is the thermal heat flow of the heat exchanger, $h_{h\_ex\_out}$ - steam/water enthalpy at heat exchanger outlet, $h_{h\_ex\_in}$ - steam/water enthalpy at heat exchanger inlet, m_s - steam/water mass flow.

The heat exchanger surface is proportional to the thermal heat flow. The method used to calculate the surfaces of all heat exchangers is the Log Mean Temperature Difference (also known as LMTD) [5], defined by the formulas:

$$LMTD = \frac{\int_A^B \Delta T(z) \cdot dz}{\int_A^B dz} \tag{8}$$

$$Q = k \cdot S \cdot LMTD, \text{ kW} \tag{9}$$

where Q is the thermal heat flow, k is the heat transfer coefficient and S is the heat exchange area.

The investment costs for this WHR system are computed following the assumptions: all tubes used for the heat exchangers have the same diameter and wall thickness; tube weight is calculated according to EN 10220; piping, pumps, auxiliary equipment, installation and commissioning are 40% of the heat exchangers price; the price for the steam turbine is calculated in euro/kW.
The chemical composition of the flue gas used in this simulation is: CO_2 – 6.7%; H_2O – 5.2%; O_2 – 11.2%; N_2 – 76.9%.

By following the basic concept of evolutionary algorithms (Fig. 3.), the initial population is defined as following: steam pressure; superheater approach temperature; economizer pinch temperature; economizer approach temperature.

Input parameters for HRSG

Stream	Parameters	Values
exhaust gas flow [kg/s]	m_g	35,67
exhaust gas temperature at HRSG inlet [°C]	t_g	360
exhaust gas temperature at HRSG outlet [°C]	t_{ev}	160
feedwater temperature [°C]	t_{dea}	145
feedwater pressure [bar]	p_{dea}	4,15

For these four parameters to fit the thermodynamic model, the function must be constraint dependent. Thus, the steam pressure variation is limited within 5-100 bar for design considerations while the superheater approach temperature limited from 15 to 30 °C, the economizer pinch from 8 to 10 °C and approach temperatures from 6 to 8 °C for thermal and economic considerations.

Selection is done according to the raw fitness score and the selection function is stochastic uniform. Reproduction has an elite count of 2 and a crossover fraction of 0.8while mutation is set to be constraint dependent [6].

Arithmetic crossover places the offspring on the line between the parents while migration takes place towards the last sub-population. The stopping criterion is set for a number of 300 generations.

4. Results and Conclusions

A first evaluation of the system takes into account the heat exchangers surface. The same criterion is for elite count, crossover and mutation is applied trough-out the simulation. The fitness function considers as variables in the optimization process:
− steam pressure (1); superheater approach (2);
− economizer pinch (3); economizer approach (4).

After computing the thermal heat flow for each heat exchanger and applying the LMTD method, optimization is done with the purpose of obtaining the lowest value for heat exchangers surface.

The program is set to stop after 300 generations, although after the 50th generation the results repeat themselves. By continuing the simulation after the 50th generation the solution is stabilized, thus ensuring that no unexpected variations will occur at any point.

Results are shown in Figure 3, showing in the upper graph the variations in the fitness value trough out the generation, and the final optimal value for the heat exchanger surface.

In the graph bellow the final value for the variables of the fitness function are listed as "best individuals".
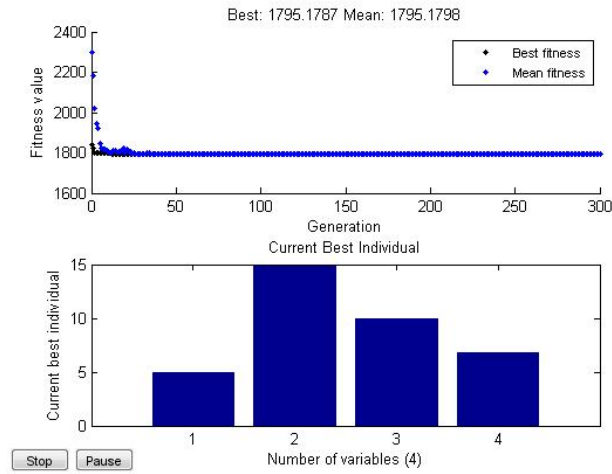
Fig. 3. Results for heat exchangers surface optimization

For a thermal and economical optimization we need to take into account also the main component – the electrical power provided by the steam turbine. Basically, after computing the thermal flow in the HRSG, we use the data to compute the value for power output.

Because the exhaust gas temperature ant HRSG inlet is set at 300°C, for safety reasons, the vapor fraction must be taken into account. This is set as a "if" function that stops the simulation for a value of less than 0,9.

The genetic algorithm optimizes by searching for the lowest value. Thus, the output value is set for negative power. Results are shown in Fig. 4.
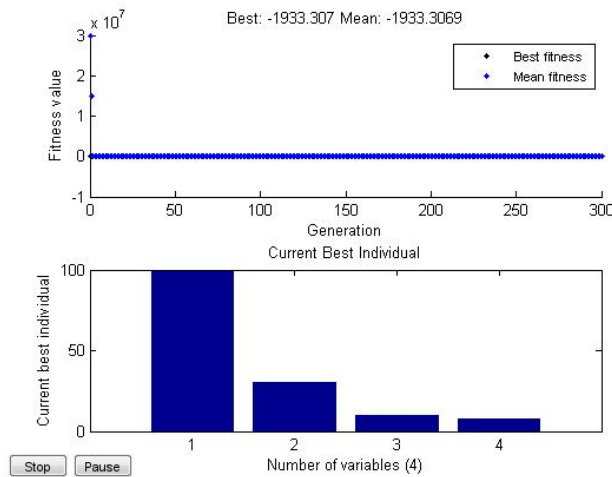

Fig. 4. Results for power output optimization

With these results set we can continue on simulating the main goal of the paper by combining the financial values with the technical optimization.

By adding values for steel price, piping, pumps, auxiliary equipment, installation, commissioning and a price for the steam turbine, calculated in euro/kW a complete picture is offered. The financial stress depends first on the heat exchanger surface, and afterwards on the power output.

The output value of the fitness function is price(euro)/kWe, for a system that runs 7500 hours/year for a period of 20 years. Results are shown in Figure 5.
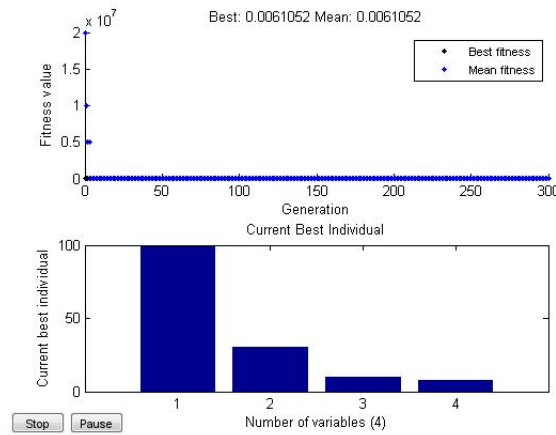
Fig. 5. Results for thermo-economic optimization

Keep in mind that the prices used in this simulation are estimates and used only with the purpose of showing the impact of different layouts on the system.

Acknowledgement

R E F E R E N C E S

[1] *D. Gewald, A. Schuster, H. Spliethoff, and N. König*, "Integrated system approach for increase of engine combined cycle efficiency", Energy Conversion and Management dedicated to ECOS 2011, Volume 60, August 2012, Pages 36–44
[2] *A.Ragland*, W. Stenzel, "Combined Cycle Heat Recovery Optimization", Proceedings of International Joint Power Generation Conference, Miami Beach, Florida, July 23-26, 2000
[3] *R. V. Serth,* Process Heat Transfer Principles and Applications. Ed. Elsevier, 2007
[4] http://www.iapws.org/
[5] *K. L. Wong, M. T. Ke, S. Ku*, "The log mean heat transfer rate method of heat exchanger considering the influence of heat radiation", Energy Conversion and Management, Volume 50, Issue 11, November 2009, Pages 2693–2698
[6] *R. L. Haupt and S. E. Haupt*, Practical Genetic Algorithms, John Wiley & Sons, 2004.