Energy 147 (2018) 36–50

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Thermodynamic efficiency improvement of combined cycle power plant's bottom cycle based on organic working fluids

Stjepko Katulić*, Mislav Čehil, Daniel Rolph Schneider

*Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10000 Zagreb, Croatia*

ARTICLE INFO

*Article history:*
Received 10 June 2017
Received in revised form
4 January 2018
Accepted 4 January 2018

*Keywords:*
Heat-exchangers network
Heat recovery steam generator
Organic cycle
Steam cycle
Thermodynamic optimization

ABSTRACT

This paper presents thermodynamic optimization of a bottom cycle which uses water and organic fluids as working fluids. The heat recovery steam generator is modeled with regard to different pressure levels, including the reheat of first pressure level, the configurations of heat-exchangers network where heat can be exchanged between flue gas and working fluids. Water is chosen as the working fluid of the first pressure level while an organic fluid for the second pressure level. Thermodynamic optimization of efficiency of the bottom cycle was conducted considering the variables of the heat-exchangers' inside the heat recovery steam generator HRSG and the operating parameters of working fluid of each pressure level and reheat. A genetic algorithm and a gradient optimization method were used with the thermodynamic model implanted in Matlab. It is shown that by using parallel and serial configurations of heat-exchangers and water in the first level pressure and organic working fluids in the second pressure level a better thermodynamic efficiency of the bottom cycle can be achieved.

## 1. Introduction

The consumption of fossil energy sources is still far greater than the energy consumption from renewable energy sources. As an example, the total consumption of primary energy sources in the United States [1] is showing that oil, natural gas and coal are the most used primary energy sources, and the average annual increase in oil consumption is about 1.5%, in coal 3.24% and in natural gas more than 4% in the period from 2000 to 2011. The generation of electrical energy from the fossil energy sources is also far greater compared to generation from renewable energy sources. The projections of consumption of primary energy sources for electricity generation in the United States [2] show their increasing tendency, and natural gas will be the most used for electricity generation with the total share of around 35% by the 2040. These data indicate that the generation of electricity using combined cycle power plants (CCPP) will continue to increase in the future.

The need to improve the thermodynamic efficiency of the CCPP is emerging as one of the measures to increase energy efficiency and reduce greenhouse gas emissions. Generally speaking, waste heat recovery and utilization represents opportunity to reduce total energy use and to decrease $CO_2$ emissions [3]. Particularly interesting is the increase of the CCPP thermodynamic efficiency ($\eta_{CCPP}$) by proper arrangement of heat-exchangers' layout in HRSG, proper selection of number of pressure levels, adequate selection of working fluids and operating parameters in order to increase thermodynamic efficiency of steam turbine part of the power plant ($\eta_{ST}$). By finding optimum values of previously mentioned variables, for the same amount of generated electricity less fuel would be consumed and therefore less greenhouse gases would be produced. According to the scientific literature review, research of increasing $\eta_{CCPP}$ can be roughly divided into three categories:

a) research of increasing the thermodynamic efficiency of both the top cycle ($\eta_{GT}$) and bottom cycle ($\eta_{ST}$) [4],
b) research of increasing $\eta_{CCPP}$ by simultaneously increasing the thermodynamic efficiency of both cycles (top and bottom) [5],
c) research of organic fluids and their impact on $\eta_{ST}$ [6].

Higher inlet temperatures, at the gas turbine inlet, resulted in higher $\eta_{GT}$ [7]. Modern steam-turbine power plants, which are part of the CCPP, use water at lower pressure levels, which somewhat reduced negative effect of a pinch point. The problem of using water in the lower pressure levels is that water at lower heat source temperatures has low $\eta_{SC}$ because, in that case, operating parameters (pressure and temperature) are also low. By introducing the

---

* Corresponding author.
*E-mail address:* stjepko.katulic@fsb.hr (S. Katulić).

https://doi.org/10.1016/j.energy.2018.01.033

complex HRSG configurations to a power plant, it became necessary to use advanced optimization methods, which made possible to find optimal operating parameters of the HRSG depending on the objective function. Manassaldi et al. [8] made superstructure that embeds different alternative HRSG configurations. The objective functions were a) The total net power generation, b) total heat transfer area. It can be concluded from the paper that the layout of the heat exchangers was not an optimization variable handled by the optimization algorithm. The proposed configurations did not have. Authors did not use parallel heat-exchanger's accommodation which is also less complex configuration and therefore optimal solution cannot be found. Also, and it is not clear why flue gas temperature at the HRSG outlet (stack temperature) is so high. By using an optimal layout for the heat exchanger, the optimal operating parameter of stack temperature should be between 60 and 70 °C. Mehrgoo et al. [9] have shown how to simultaneously optimize the operating and geometric design parameters of the HRSG by using the constructal theory. The objective function was the total entropy generation. Author's did not optimize heat-exchanger's layout. Zhang et al. [10] optimized operation of HRSG coupled with external heat-exchangers. HRSG was divided into several sub-units. The position of the heat exchanger was determined by binary variables. That means that the position of the heat-exchanger can be (if it exist) only at an advanced determined location. Also, location of evaporator was fixed which is certain limitation if optimal solution wants to be found. The mass flow rate of the first pressure level can be determined using the mass and energy equilibrium equations so that it is not clear why it was selected as an optimization variable. Proposed HRSG configurations do not have heat-exchanger's in their mutual parallel position which proved to be disadvantage if optimal thermodynamic efficiency of a plant wants to be obtained. Li et al. [11] presented a method for waste heat utilization. Objective function was the net power output. Different cycle configurations were evaluated, in addition working fluid selection among the organic fluids was performed. The optimization of heat-exchanger's layout was not in the scope of their work. The results indicate that the regenerative organic transcritical cycle produces the maximum power output at source temperatures up to about 500 °C. Nadir and Ghenaiet [12] compared three different HRSG configurations operating at exhaust gas temperature from 350 °C to 650 °C. The optimization variables were operating parameters (pressure, temperature) but not the heat-exchanger's layout. In their paper stack temperature was 96 °C which is too high compared to well optimized heat-exchanger's layout and operating parameters. Valdes et al. [13] optimized the combined cycle with multi pressure HRSG using the cost of production per unit of generated electricity and annual cash flow as an objective function. Bassily [14]] conducted numerical cost optimization and irreversibility analysis of CCPP with triple pressure HRSG. Operating parameters and the irreversibilities of the components were analyzed. Koch et al. [15] applied an evolutionary algorithm to the minimization of the product cost of CCPP. Authors analyzed CCPP with two-pressure HRSG with a reheater. Authors concluded that exergy is closely related to the economic value of an energy carrier. Valdes and Rapun [16] presented a method for the optimization of the HRSG based on the application of influence coefficients. Authors concluded that application of influence coefficients to the thermal system design permits better understanding of the effects of the modifications in the variables of these systems. Katovicz and Bart [17] optimized HRSG with three pressure levels and a reheater, analyzing influence of the fuel price on the optimum operating parameters. The objective function was the net present value of investment. Xiang et al. [18] reported that today's $\eta_{ST}$ reaches thermodynamic efficiency of 39.2%. The methodology which they applied for calculating thermodynamic efficiency was not mentioned. Čehil et al. [19] presented a novel method for determining optimal heat-exchanger layouts for HRSG. The method considers all possible heat-exchanger layouts, of each pressure level, both in serial and parallel arrangement and water was working fluid. The maximum $\eta_{ST}$ was set as the objective function. Bianchi et al. [20] focused on an innovative strategy to improve waste heat conversion through the integration of a conventional waste-to-heat power plant with a gas turbine. Authors carried out parametric analysis of the effect of the discharged heat, from a gas turbine, on the steam mass flow production in a steam generator. They concluded that this conventional waste-to-heat power plant provides power output increase up to 80% compared to mid-size reference case.

Recently, there is a growing interest in exergoeconomic optimization of power plant operation, especially of cogeneration systems [21], systems with renewable energy sources [22] and thermal power plants with coal as the primary fuel source [23]. Nadir et al. [24] conducted thermo-economic optimization of different HRSG configurations for gas turbine outlet temperatures ranging from 350 °C to 650 °C. The obtained results were used to elaborate correlation between net present value and gas turbine outlet temperature, flue gas mass flow rate, electricity selling price and number of pressure levels of HRSG. Petrakopoulou et al. [25] conducted a comprehensive exergy analysis to determine the potential benefits of using the system with triple pressure HRSG. Carapelluci and Giordano [26] compared two methods for optimizing the operating parameters of CCPP: a) minimizing the cost per unit of generated electricity and b) minimizing the objective function which represents exergoeconomic losses associated with inefficiencies of thermodynamic processes. Optimization was performed for different configurations of HRSG (different number of pressure levels), different gas turbines and different fuel prices. Bakhshmand et al. [27] conducted exergoeconomic analysis and optimization of CCPP with triple-pressure HRSG and with a reheater. The objective function was the total cost rate of the power plant. Once again, authors did not optimize heat-exchanger's layout. Sharma and Singh [28] performed exergy analysis of dual-pressure HRSG. Different physical parameters of HRSG such as fin height, fin density and fin thickness were varied for analyzing exergy efficiency at different operating pressures. Authors also presented in Ref. [29] exergy analysis of dual-pressure HRSG for varying dead states. Particular sections of the HRSG having maximum exergy losses have been located. Naemi et al. [30] performed thermodynamic and thermoeconomic analysis of dual-pressure HRSG coupled with gas turbine in order to achieve optimum operating parameters. Heat-exchanger's were only in serial arrangement.

A power plant with a gas turbine in the top cycle generally has water as working fluid in the bottom cycle because water has good physical and thermodynamic properties at high temperatures and is easily accessible. In systems in which the heat source is at lower temperatures, it is possible to use other working fluids such as a mixture of water and ammonia in a process known as the Kalina cycle [6]. Generally, it can be said that at lower heat source temperatures organic Rankine cycle (ORC) is an alternative to the water in the CCPP's bottom cycle because it has better thermodynamic properties [31]. Marrero et al. [32] conducted optimization of a combined triple power cycle (gas-steam-ammonia). They concluded that the ammonia bottoming cycle provides a more efficient thermal matching for the triple cycle HRSG than the HRSG of a conventional combined cycle. Carcasci et al. [33] have investigated the impact of the working fluid such as: toluene, benzene, cyclohexane and cyclopentane selection on utilization of flue gas heat at the gas heat from a turbine outlet. HRSG had only one pressure level. Chacartegui et al. [34] investigated the use of