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A discrete and continuous mathematical model for the optimal synthesis and design of dual pressure heat recovery steam generators coupled to two steam turbines

Juan I. Manassaldi [a], Ana M. Arias [a], Nicolás J. Scenna [a], Miguel C. Mussati [a, b], Sergio F. Mussati [a, b, *]

[a] CAIMI Centro de Aplicaciones Informáticas y Modelado en Ingeniería (Universidad Tecnológica Nacional, Facultad Regional Rosario), Zeballos 1346, S2000BQA Rosario, Argentina
[b] INGAR Instituto de Desarrollo y Diseño (CONICET-UTN), Avellaneda 3657, S3002GJC Santa Fe, Argentina

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ABSTRACT

This paper addresses the optimal arrangement and design of a dual pressure heat recovery steam generator coupled to two steam turbines. A superstructure that embeds various alternative configurations is optimized considering the following two single objective functions: (a) the maximization of the total net power generation for a given total heat transfer area and (b) the minimization of the total heat transfer area for a given total net power. The optimal number of heat exchangers and pumps and how they should be connected are the discrete decisions. The dimensions and operating conditions are the continuous decisions. A discrete and continuous mathematical model is developed and logical propositions are used for discrete decisions. The results are compared with a reference case reported by other authors. The results indicated that the optimization of the proposed superstructure allowed to find a more efficient HRSG configuration. The obtained configurations differ from the configuration of the reference case in how the heat exchangers and pumps are connected. A considerable increase in about 8% of the total net power generation in (a) and a significant reduction in about 24% of the total heat transfer area in (b) are achieved when compared to the reference case.

1. Introduction

Compared to the conventional steam and/or gas turbine power plants, the CCPPs (combined cycle power plants) offer higher thermal efficiency and are less environmental impact. In a typical combined cycle the HRSG (heat recovery steam generator) is considered to be the most important process-unit because is the link between the gas turbine-based topping cycle and steam turbine-based bottoming cycle. In the HRSG, the heat of the hot exhaust gas produced by the gas turbine is recovered and is used to convert water into steam which is then used by the steam turbines to produce power. The overall performance of the CCPPs depends strongly on how efficient the HRSG design is. The main goal and contribution of this paper is focused on the development of a mathematical model which allows the simultaneous optimization of the arrangement, size and operating conditions of the HRSG in order to optimize a given objective function. Precisely, two single objective functions are considered in order to show the applicability of the proposed model: a) the minimization of the THTA (total heat transfer area) for a fixed TNP (total net power) and b) the maximization of the TNP for a fixed THTA.

In the literature, there are many papers published addressing the mathematical modeling and optimization of heat and power plants including combined cycles. This is because of the different levels of complexity and assumptions used to derive mathematical models as design specifications are assumed, several analysis methodologies and/or optimization approaches are employed.

During the last time, several techniques based on the second law of thermodynamics, such as exergy analysis and exergoeconomic analyses have been applied in energy conversion systems.

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* Corresponding author. INGAR Instituto de Desarrollo y Diseño (CONICET-UTN), Avellaneda 3657, S3002GJC Santa Fe, Argentina. Tel.: +54 342 4534451; fax: +54 342 4553439.
E-mail address: mussati@santafe-conicet.gov.ar (S.F. Mussati).

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Exergy analysis is usually applied in a systematic way and it allows the localization and account of the inefficiency degree indicating the most inefficient components in a system. These values can be then used in the decision-making process, for instance in the retrofit of processes in order to improve the already existing process by switching out or by introducing components that involve low irreversibility. This can contribute to improvements of the thermal system as a whole or at a component level. In some cases, the exergy analysis can accurately assess the locations of inefficiencies than energy analysis. Mansouri et al. [1] investigated the effect of HRSG (heat recovery steam generator) pressure levels on exergy efficiency of combined cycle power plants and show that increases in the number of pressure levels of the HRSG affect the exergy losses due to heat transfer in the HRSG and the exhaust of flue gas to the stack. By applying the exergy analysis, Sanjay [2] investigated the effect of operating parameters on the rational efficiency and exergy destruction of combined cycle and showed that higher turbine inlet temperature and higher compressor pressure ratio is favorable on the performance of combined cycle. Regulagadda et al. [3] conducted a parametric study of a thermal power plant under various operating conditions, including different operating pressures, temperatures and flow rates, in order to determine the parameters that maximize plant performance. The exergy loss distribution indicates that boiler and turbine irreversibility yield the highest exergy losses in the power plant. Tsatsaronis et al. [4] proposed to split the exergy destruction into avoidable and unavoidable parts and demonstrate the advantages of dividing exergy destruction and economic costs into avoidable and unavoidable parts on the example of co-generative plants. Morosuk et al. [5] introduced how to calculate the parts of exergy destruction in an advanced exergy analysis which was applied to a simple gas-turbine system and they showed the potential for improvement and the interactions among the system components. Also, Tsatsatorins et al. [6] applied the advanced exergetic analysis of a novel system for generating electricity and vaporizing liquefied natural gas. The authors concluded that the application of the advanced analysis allows to obtain new improvement strategies. As the rate of exergy destruction in component A not only depends on its exergetic efficiency but also on the exergetic efficiency of the remaining components, structural coefficients are usually introduced in order to consider how local irreversibilities in the components affect the overall irreversibility rate of the cycle. These structural coefficients can only be evaluated once the irreversibilities of the components and the whole cycle are known (evaluated). Therefore, the calculation of these coefficients may require a high number of simulation runs resulting in time-consuming procedure ([7]). Certainly the simulation runs required when the process involves many unit-processes and, moreover, when the optimization problem to be solved is highly combinatorial (high number of discrete decisions) may increase drastically. Some of the recent applications of the exergy analysis in energy conversion systems can be found in Refs. [8–11].

On the other hand, thermoeconomics, also called exergoeconomics, is the combination of exergy and conventional economics. The thermoeconomic cost balance is formulated in the same way as the exergy balance but including the investment CAPEX (capital expenditure) and O&M (operating and maintenance) costs of the entire process. One of the purposes of this method is to be able to distinguish between production costs of different products, e.g. cogeneration of both heat and power. It is also used for the evaluation of cost streams and the cost of exergy destruction for individual components or the system as a whole. Exergoeconomic methods may be grouped in algebraic methods and calculus methods [12,13]. The algebraic methods use algebraic balance equations and it requires to propose auxiliary cost equations for each component which represent a subjective task. On the other hand, calculus methods use differential equations, where the system cost flows are obtained in conjunction with optimization procedures based on the method of Lagrange multipliers, which determines marginal cost. In this method, the mathematical description of the function of each component is also subjective. Based on the exergoeconomic principles, Bhargava et al. [14] analyzed a cogeneration system consisting of an intercooled reheat gas turbine, with and without recuperation. Their result provided useful guidelines for preliminary sizing and selection of gas turbine cycle for cogeneration applications. Recently, Bakhshmand et al. [15] performed an exergoeconomic analysis and optimization of a combined power plant with triple-pressure including one reheating stage. To do this, the authors implemented a simulation code in MATLAB employing an evolutionary algorithm. The objective function includes both product cost rate and cost rates associated with exergy destructions. The obtained results allowed to the authors to propose optimal criteria of performance for the studied process. It should be noted that such methodology is applicable to optimize steady state operation parameters of given CCPP, and it is not suitable to optimize the design of projected systems.

Most of the conventional exergy and exergo-economic optimization methods are iterative and subjective in nature because they require the interpretation of the designer at each iteration to determine the final configuration [16].

On the other hand, motivated by the maturity of the design-optimization methods and software as well as the advent of powerful modern computational platforms there is a really renewed interest in the application of mathematical programming and rigorous optimization approaches in a variety of industrial sectors, including the area of utility plants and combined heat and power systems. Thus, there is a great variety of interesting articles addressing different optimization mathematical models considering both discrete and continuous decisions for different optimization purposes and different ways to treat the uncertainties of the models. In fact, advanced optimization approaches and mathematical models with high number of non-linear constraints and variables have already been applied to numerous problems for achieving improvements in “real-world” heat and power designs.

There are a great variety of articles that have been recently published where classical non-deterministic and deterministic techniques are applied. Certainly, there is a great number of articles that focus on the application of SA (simulated annealing) and GA (genetic algorithms) and deterministic MINLP techniques energy conversion systems.

Simulated Annealing and Genetic Algorithm are two well-known metaheuristic algorithms for combinatorial optimization. Simulated annealing is based on a simple local search algorithm proceeds by choosing random initial solution and generating a neighbor from that solution. They are derivate-free and are well suited for high complexity problems with discontinues models and without any known sophisticated solution techniques like the combinatorial optimization problems. The optimal solutions obtained by the two algorithms are strongly dependent on the parameters required by the two algorithms. For instance, in GA, the number of generations, population, crossover rate, mutation rate and tournament size (number of individuals needed to fill a tournament during selection). In addition they are inherently sequential and hence very slow for problems with large search spaces. Both, algorithms have been successfully applied in power plants where the configurations of process-units are known (fixed).

On the other hand, the deterministic MINLP optimizations, which will be adopted in this paper, are well suitable for mathematically modeling many optimization problems that involve both