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Optimal design of process energy systems integrating sustainable considerations

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ABSTRACT

In this paper is presented a novel approach for designing sustainable trigeneration systems (i.e., heating, cooling and power generation cycles) integrated with heat exchanger networks and accounting simultaneously for economic, environmental and social issues. The trigeneration system is comprised of steam and organic Rankine cycles and an absorption refrigeration cycle. Multiple sustainable energy sources such as solar energy, biofuels and fossil fuels are considered to drive the steam Rankine cycle. The model is aimed to select the optimal working fluid to operate the organic Rankine cycle and to determine the optimal system to operate the absorption refrigeration cycle. The residual energy available in the steam Rankine cycle and/or the process excess heat can be employed to run both the organic Rankine cycle and the absorption refrigeration cycle to produce electricity and refrigeration below the ambient temperature, respectively. Two example problems are presented to show the applicability of the proposed methodology.

1. Introduction

Nowadays energy is one of the most important resources and at the same time one of the most relevant concerns around the world owing to fast depletion of non-renewable fuels, the global warming and the climate change. For these reasons, several governments have promoted the use of cleaner energies through tax credits and there have been invested significant economic resources to searching for alternative energies to mitigate the environmental issues [1]. In this sense, power plants and industries consume enormous amounts of fossil fuels to satisfy the electricity and utilities demands. Since few decades ago, several researches prioritized this topic and focused their investigations on the maximization of recovery process heat through the minimization of external utilities using HENs (heat exchanger networks), where there are some streams requiring cooling and others needing heating (see the paper review by Morar and Agachi [2]). Nonetheless, previous approaches have been concentrated in synthesizing HENs without considering the energy interactions among the HEN and the associated utility system.

Moreover, nowadays there are significant environmental, economic and social concerns about the utility systems; this mainly associated to the depletion of natural resources, socio-economic development and global climate change due to GHGE (greenhouse gas emissions), especially CO_2 emissions associated with the use of fossil fuels. Furthermore, when the economic and environmental criteria are prioritized together with social aspects, sustainable processes are generated. Recently, industrial processes have been addressed to consider the three aspects of sustainability for a holistic development. In this context, significant socio-economic and environmental benefits can be achieved through the optimal synthesis of trigeneration systems (i.e., cogeneration systems for combined heat, cooling and power production) that are integrated with HEN and use renewable energy resources as primary heat sources to reduce fossil fuel consumption and GHGE. Therefore, the objective of this paper is to present a mathematical formulation for the simultaneous synthesis of sustainable trigeneration systems and HEN, where the optimal working fluid to operate the ORC (organic Rankine cycle) is determined as well as the optimal system to run the AR (absorption refrigeration) cycle, considering the energy interaction among the different subsystems

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accounted. In this regard, the proposed integrated formulation takes into account a set of HPS (hot process streams) and a set of CPS (cold process streams), as well as three thermodynamic cycles: single-effect AR cycle to supply below ambient cooling, a SRC (steam Rankine cycle) and an ORC to produce electricity. The proposed mathematical model is based on a superstructure that includes the main feasible heat integration options and connections between the system components. The synthesis problem is formulated as a multi-objective MINLP (mixed-integer nonlinear programming) problem with economic, environmental and social concerns of sustainability. The environmental objective is evaluated by the overall GHGE, and the social objective is quantified by the number of generated jobs. The multi-objective optimization model is solved with the ε-constraint method. The optimal solutions yield a Pareto set that shows the tradeoffs between the total annual profit, the GHGE and the number of generated jobs in the entire life cycle of the integrated energy system. The capabilities of the proposed approach are illustrated through its application to two example problems. The results indicate that the integration of HEN and trigeneration schemes yields energy savings and more environmental benign solutions.

2. Literature review

The methodologies for synthesizing HENs have been classified in the following categories: sequential approaches using the pinch analysis (i.e., considering the energy-capital tradeoff [3] and targets for network area and pumping cost [4]), stochastic methods (Lotfi [5] included the non-isothermal mixing of streams and Ponce-Ortega et al. [6] took into account the detailed design of each heat exchange unit) and mathematical programming-based techniques (in this case a novel superstructure was proposed by Yee and Grossmann [7], while Ponce-Ortega et al. [8] incorporated isothermal process streams, additionally Ponce-Ortega et al. [9] involved multiple utilities, Huang et al. [10] considered non-isothermal mixing and Manassaldi et al. [11] incorporated air coolers). Other methodologies have taken into account the energy integration among power cycles and HEN as well as with a utility system, which have been based on thermodynamic principles and heuristic rules. In this sense, Townsend and Linnhoff [12] presented rules for the appropriate placement of heat pumps and engines in process networks relative to the heat recovery pinch, Maréchal and Kalitventzeff [13] proposed a procedure for computing the integrated combined heat and power target of industrial processes based on the analysis of the shape of the balanced grand composite curves and improved the qualitative guidelines for positioning combined heat and power engines, and Desai and Bandyopadhyay [14] developed a sequential method based on pinch analysis for integrating ORC with processes to generate power and, at the same time, to reduce the overall consumption of cold utility. Additionally, others methodologies have employed optimization techniques for the problem of heat and power integration with the process and utility systems; thus, Papoulias and Grossmann [15] presented a MILP (mixed-integer linear programming) formulation for the optimal synthesis of total processing systems consisting of a chemical plant, with its HEN and utility system, including a novel superstructure-based method for the synthesis of heat and power integration in process networks, Colmenares and Seider [16] developed a NLP (non-linear programming) strategy for integrating heat engines and heat pumps with the process heat cascade, Lee et al. [17] performed a thermodynamic analysis of an IGCC (integrated gasification combined cycle) plant to determine the key components, Swaney [18] proposed an extended transportation array formulation for designing process heat recovery networks incorporating Rankine cycles and heat pumps, Holiastos and Manousiouthakis [19] introduced a mathematical formulation for the optimal integration of heat exchangers, heat engines and heat pumps in HEN, Chen and Lin [20] formulated a MINLP model for synthesizing an entire energy system, which includes the interactions between the steam network and the HEN of process plants, and Hipólito-Valencia et al. [21] designed a MINLP formulation based on an integrated stage-wise superstructure to simultaneously determine the optimal configuration, design parameters and operating conditions of integrated energy systems that consist of a HEN and an ORC. In this context, ORC is a novel strategy to take residual heat to produce electricity. In addition, recently several studies have been reported for improving ORCs; this way, Vélez et al. [22] presented an overview of the technical and economic aspects associated to ORCs, Pan [23] carried out an analysis for the performance of ORC near-critical conditions, Schuster et al. [24] optimized the working fluid in supercritical conditions for ORC, Mohammadkhani et al. [25] implemented an exergoeconomic analysis for a combined system in which waste heat is utilized by two ORCs, Srinivasan et al. [26] examined the reuse of waste heat of high efficiency low temperature combustion engine through an ORC, and Astolfi et al. [27] investigated the feasibility of ORC through an economic optimization.

Moreover, a significant number of methodologies have aimed their efforts to find the optimal organic working fluid to operate properly an ORC with different methods, such as carrying out a parametric optimization [28], using the pinch point and exergy analysis [29], for different energy levels [30], at sub or supercritical pressures [31], investigating the effect of the fluid boiling point temperature on the overall performance [32], considering pure and mixture working fluids [33], as well as combining ORCs with a heat recovery vapor generator [34] or a gas turbine [35]. Nevertheless, these approaches have not considered the optimal selection of the working fluid for an ORC interacting energetically at the same time with a HEN and other thermodynamic cycles.

Afterwards, a graphical method based on the total site profiles, which is an extension of pinch analysis, has played an important role in solving the problem of heat and power integration in a set of processes served by a central utility system. This method was called the total site analysis and it was introduced by Dhole and Linnhoff [36], while Raissi [37] used this methodology for targeting of energy recovery, heat and power cogeneration and emissions from utility systems. Later, this approach has been widely employed by other authors (see Klemeš et al. [38]). Furthermore, Bagajewicz and Barbaro [39] presented non-linear targeting models to get maximum cost savings and optimum integration of heat pumps in total sites, Varbanov et al. [40] applied the total site analysis to address the steam system design with the total site integration considering the reduction of GHGE, whereas Perry et al. [41] used this method to reduce carbon footprint through integration of renewable energy sources, and Varbanov and Klemeš [42] included the variations in the energy supplies and demands.

On the other hand, there are several industrial processes requiring cooling above ambient temperature; in this regard, regularly re-circulating cooling water systems are used to provide the required cold utility. Several methodologies have been published considering the interactions between cooling systems and processes [43]; this way, the cooling tower is designed together with the synthesis of the associated HEN or cooling water network [44]. Additionally, some strategies have been reported for processes that require cooling below ambient temperature. In this way, recently Ponce-Ortega et al. [45] published mathematical programming-based approaches to address the problem of multi-objective optimization of AR cycles that are integrated with HEN, and then Lira-Barragán et al. [46] incorporated sustainability criteria. In these integrated energy systems, the AR cycle uses