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Simultaneous synthesis of work exchange networks with heat integration

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HIGHLIGHTS

- New MINLP model for the synthesis of work exchange networks with heat integration.
- Work integration of streams at high and low-pressure in a multi-stage superstructure.
- Pressure manipulation equipment acting on several shafts and stand-alone equipment.
- Heat integration between pressure manipulation stages in the work exchange network.
- Use of a smaller amount of utilities reducing capital cost and operational expenses.

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ABSTRACT

The optimal integration of work and its interaction with heat can represent large energy savings in industrial plants. This paper introduces a new optimization model for the simultaneous synthesis of work exchange networks (WENs), with heat integration for the optimal pressure recovery of process gaseous streams. The proposed approach for the WEN synthesis is analogous to the well-known problem of synthesis of heat exchanger networks (HENs). Thus, there is work exchange between high-pressure (HP) and low-pressure (LP) streams, achieved by pressure manipulation equipment running on common axes. The model allows the use of several units of single-shaft-turbine-compressor (SSTC), as well as stand-alone compressors, turbines and valves. Helper motors and generators are used to respond to any demand and excess of energy. Moreover, between the WEN stages the streams are sent to the HEN to promote thermal recovery, aiming to enhance the work integration. A multi-stage superstructure is proposed to represent the process. The WEN superstructure is optimized in a mixed-integer nonlinear programming (MINLP) formulation and solved with the GAMS software, with the goal of minimizing the total annualized cost. Three examples are conducted to verify the accuracy of the proposed method. In all case studies, the heat integration between WEN stages is essential to improve the pressure recovery, and to reduce the total costs involved in the process.

1. Introduction

The energy efficiency is crucial in transformation processes, since it is responsible for a large portion of expenditures and acts decisively on environmental aspects. One of the main reasons to develop techniques for efficient and sustainable energy use is the increasing global demand, allied to the high cost of energy due to the rapid decrease in the availability of fossil fuels. Other significant reasons include the technological barriers and forbidding prices of renewable energy, the strict standards that regulate carbon dioxide emissions, as an attempt to palliate the greenhouse effect and its consequences (Gharaie et al., 2013; Hasan et al., 2010; Huang and Karimi, 2013; Razib et al., 2012; Wechsung et al., 2011). The minimization of environmental impacts can be achieved by increasing energy efficiency in industrial plants, particularly through the reduction of energy consumption, adoption of innovative strategies and development of more efficient processing techniques (Lara et al., 2013; Morar and Agachi, 2010).

The optimization of heat recovery is critical to solve the problem of the efficient use of energy and, consequently, to promote the reduction of gaseous emissions and consumption of oil and natural

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gas, since the reduction of energy consumption is closely linked to improvement of heat transfer (Cheng and Liang, 2012a; Kaluri and Basak, 2011; Onishi et al., 2013; Wang et al., 2011). Thereby, harnessing energy from process streams through thermal integration between heat exchangers and cooling and/or heating systems is one of the most effective ways to reduce costs. The optimal synthesis of heat exchanger networks (HENs) consists in promoting the thermal integration of the system via an efficient network design, in economic and thermodynamic terms, in which the number of heat exchangers units and utilities consumption is minimal. This result can be obtained by minimizing the heat exchange area (Gorji-Bandpy et al., 2011; Serna and Jiménez, 2004), and/or the total cost of the HEN—relative to the cost of capital investment in the units of the network and operational expenses (Al-mutairi, 2010; Björk and Nordman, 2005; Escobar and Trierweiler, 2013; Frausto-Hernández et al., 2003; Huang and Karimi, 2013; Ravagnani and Caballero, 2007; Serna-González and Ponce-Ortega, 2011; Sors and Kravanja, 2002; Vaskan et al., 2012), and/or by minimizing other parameters such as exergy or entropy of the system (Cheng and Liang, 2012b, 2012c; Wechsung et al., 2011).

The HEN is essential in many industrial processes, including food and pharmaceutical industries, chemical plants, distillation of crude oil and cooling water systems. These industries are responsible for the consumption of large amounts of energy, being the process of heat transfer one of the most expensive (Allen et al., 2009; Vaklieva-Bancheva et al. 1996). For this reason, over the past few decades, the research in the area of HEN synthesis has received large attention from the scientific community, and significant progress has been made with considerable impact on the industry (Al-mutairi, 2010; Escobar and Trierweiler, 2013; Furman and Sahinidis, 2002; Huang and Karimi, 2013). Among the first works published with proposals to solve the problem of HEN synthesis are the papers of Hwa (1965), using separable programming methods, and Kesler and Parker (1969), using linear programming. Important literature reviews were also published by Jezowski (1994a, 1994b), Gundersen and Naess (1988), and Furman and Sahinidis (2002).

Despite the considerable effort to optimize heat integration and the outstanding results already achieved in HEN synthesis, other forms of energy are often available in processing plants such as, for example, work. Handling pressure is responsible for considerable energy consumption, and it is especially important in oil refineries, synthetic processes like ammonia and methanol synthesis, and cryogenic processes such as the production of liquefied natural gas (LNG). This source of energy—work—has been poorly explored in the process synthesis area, in spite of its higher cost in comparison with heat. In fact, compressors and turbines correspond to some of the most expensive equipment in industries, surpassing the value of heat exchange equipment. Given the urgency of achieving this important industrial goal focused on improving energy efficiency, the integration of work, and a closer interaction between work and heat should be considered as viable alternatives. Therefore, it is possible to integrate both work and heat in the same network for the purpose of energy conservation (Razib et al., 2012).

Aspelund et al. (2007) presented a heuristic graphical method based on Extended Pinch Analysis and Design (ExPAnD) to minimize energy requirements under sub-ambient conditions. In their work, compressors and turbines are used separately, and no mention is made to the use of combinations between these pressure manipulation equipment operating on a same axis. Furthermore, the economic aspects have not been examined, only the aspects related to the exergy analysis of the system were evaluated. This type of analysis can lead to processes that on one hand are highly effective, but on the other hand are economically impracticable. Moreover, it is necessary to consider that the very nature of heuristic methods can take to sub-optimal solutions.

Wechsung et al. (2011) proposed a model for the HENs synthesis, wherein the streams are subjected to pressure manipulation. The authors combine pinch analysis, exergy analysis and mathematical programming to obtain an optimal network with minimal irreversibility. In this study, an industrial application, relating to the LNG production, demonstrates that a particular route of compression and expansion of gas flows can significantly reduce the total irreversibility in HENs. In Onishi et al. (2014), a superstructure for simultaneous synthesis of HENs is presented, considering the adjustment of pressure levels of process streams to improve heat integration. The model is formulated using generalized disjunctive programming (GDP) and reformulated in mixed-integer nonlinear programming (MINLP). Several configuration possibilities involving compressors, turbines and valves are studied, with the goal of minimizing the total annualized cost of the network. The authors demonstrate that the optimal integration between heat and work can reduce the amount of necessary utilities, decreasing the costs involved in the process. However, in these works the pressure manipulation equipment were considered independently, i.e., as stand-alone equipment, or just allowing the coupling between one compressor and one turbine on a single common shaft, as in Onishi et al. (2014).

Huang and Fan (1996) define the WEN as a work exchange network between two or more transfer units, and propose the operational principles for work exchange among two streams. Razib et al. (2012) introduce the WEN terminology to denote the synthesis problem of work exchange networks, analogously to the well-studied HEN synthesis problem. An optimization model for the preliminary WEN synthesis is proposed, by formulating a superstructure in mathematical programming. The aim is the minimization of the total annual cost for a single-shaft-turbine-compressor (SSTC) running at a constant speed. Operational curves of turbines and compressors are used to identify high and low-pressure flows for the work exchange through expansion and compression stages in equipment located in a single axis unit. Nevertheless, the authors did not consider the possibility of thermal integration of the process streams, such that the heat exchange between process streams was disallowed. Thus, heaters and coolers are just arranged at the end of each stage. Moreover, the possibility of using several shafts has not been evaluated, the model is restricted to a fixed rotational speed of the shaft, and all costs are considered as linear functions, not being able to realistically translate the process costs.

The present paper introduces a new model for the synthesis of work exchange networks (WENs), with heat integration of process gaseous streams obtained by the simultaneous design of the HEN. The WEN synthesis consists in optimal work integration between streams at high-pressure (HP) and low-pressure (LP), using pressure manipulation equipment acting on a common SSTC axis and stand-alone equipment to minimize the total annualized cost. The objective function is composed by capital costs associated to the various units of the network and operational expenses. The handling pressure of streams is performed in a multi-stage superstructure, allowing the use of several shafts units. Generators and helper motors are used, respectively, to convert work excess into electricity and to fill for power shortage on the SSTC units. Between the compression and expansion stages of the WEN, the streams are sent to the HEN to promote heat integration. The HEN formulation is based on the model of Yee and Grossmann (1990), in which isothermal mixing and constant heat transfer coefficients are assumed, and the possibility of stream splits is considered. The main difference of the proposed model to the Razib et al. (2012) model relies in the thermal integration of the streams occurring simultaneously to the work integration. As a consequence, the inlet and outlet temperatures in the HEN are dependent on the WEN synthesis; thus, they should be considered as optimization