Applied Thermal Engineering 62 (2014) 633–652

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Optimal design of inter-plant waste energy integration

Brígido Jesús Hipólito-Valencia [a], Eusiel Rubio-Castro [b], José María Ponce-Ortega [a,*], Medardo Serna-González [a], Fabricio Nápoles-Rivera [a], Mahmoud M. El-Halwagi [c,d]

[a] Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia 58060, Michoacán, Mexico
[b] Chemical and Biological Sciences Department, Universidad Autónoma de Sinaloa, Culiacán 80000, Sinaloa, Mexico
[c] Chemical Engineering Department, Texas A&M University, College Station, TX, USA
[d] Chemical and Materials Engineering Department, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, P.O. Box 80204, Saudi Arabia

HIGHLIGHTS

- An optimization approach for heat integration in eco-industrial parks is proposed.
- Waste heat recovery is proposed through integrated organic Rankine cycles.
- Improved energy integration schemes are obtained with the proposed approach.

ARTICLE INFO

Article history:
Received 4 July 2013
Accepted 11 October 2013
Available online 22 October 2013

Keywords:
Waste energy recovery
Inter-plant integration
Eco-industrial parks
Heat exchanger networks
Organic Rankine cycles

ABSTRACT

In this paper, a new superstructure for heat integration of an eco-industrial park is proposed. Intra and inter-plant heat exchange for the process streams is allowed. For a proper reuse of the waste heat at low temperature, a set of organic Rankine cycles (ORCs) can be integrated inside the eco-industrial park. This way, the proposed superstructure allows proper heat integration to reduce the use of external cooling and heating utilities as well as the consumption of external electric energy. The proposed superstructure is modeled through a mathematical programming formulation where the objective function considers the simultaneous minimization of the operating and capital costs for the units involved in the system as well the possible revenues from the sales of electricity. The model is formulated in such a way that avoids numerical complications during its solution. Results from the application of the proposed approach show that the interplant-integration offers significant savings compared to the traditional single-plant integration with and without considering ORCs.

1. Introduction

Energy consumption represents a major concern in industry because of the massive requirements of external utilities such as heating, cooling and electricity. In addition to the economic aspect, the use of these utilities represents a severe environmental impact because usually fossil fuels are burned to produce electricity and hot utilities. In this context, the synthesis of heat exchanger networks (HEN) has been a very attractive option to reduce the external consumption of hot and cold utilities. The main idea of the HEN synthesis is integrating the heat of process streams by allowing heat exchanges between hot process streams (streams that need to be cooled) and cold process streams (streams that need to be heated) in such a way that the overall external heating and cooling utilities are minimized [1–4]. The selection of the allowed matches between hot and cold process streams is not trivial, and several methods have been reported to solve the synthesis of HENs. The aforementioned methods have been classified as heuristic [5–10], based on stochastic searches [11,12] and based on mathematical programming approaches [13–26]. In addition, several approaches have been reported to retrofit existing HENs [27–32]. The implementation of HENs allows reducing the external consumption of hot and cold utilities in a given plant (see Fig. 1); usually significant amounts of heat at low temperatures have to be removed using external cooling utilities [33–41]. However, this process excess heat at low temperature (i.e., waste heat) can be used as heat source for an organic Rankine cycle (ORC) to produce electric power. This way, reducing the use of external cooling utilities and, at the same time, providing part of the electric power required for the process can be achieved (see Fig. 1) [42–49]. The ORC is characterized by using an organic fluid as working fluid. In this regard, several works have focused on the selection of the working fluid, which depends

* Corresponding author. Tel.: +52 443 3223500x1277; fax: +52 443 3273584.
E-mail addresses: jmponce@umich.mx, jose_maria_ponce@yahoo.com (J.M. Ponce-Ortega).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.10.015

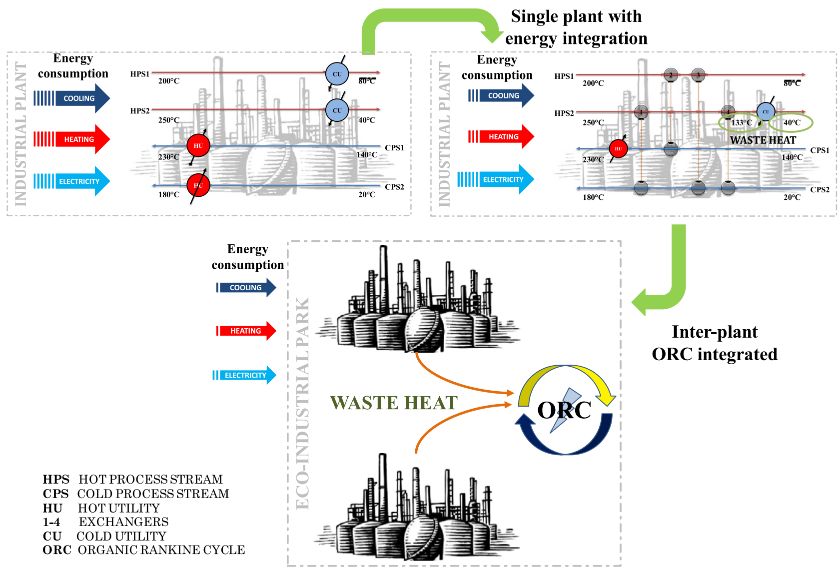

Fig. 1. Schematic representation of the addressed problem.

strongly on the considered application [50–54]. The ORC integrates four basic components: evaporator, turbine, condenser and pump; moreover, several authors add a regenerating process to increase the cycle efficiency. This way, several alternatives seem to be attractive options to integrate this excess heat, and the optimal solution is not obvious. Recently, Desai and Bandyopadhyay [55] proposed a sequential methodology for the synthesis of a HEN involving the integration of an ORC for recovering the heat excess at low temperature. This methodology helps to reduce cold utility in HENs and, at the same time, to produce power in the ORC. However, this methodology is a sequential approach based on heuristic rules that do not allow the optimal integration of the waste heat. Also, this approach does not consider the capital and operating costs for the units involved. Therefore, this approach may yield suboptimal solutions.

On the other hand, an inter-plant integration or an eco-industrial park (EIP) is defined as a community of manufacturing and service businesses seeking to enhance the environmental and economic performance through collaborating in managing environmental and resource issues including energy, water and materials. By working together, the community of businesses seeks a greater collective benefit than the sum of the individual benefit for each company [56]. Examples of EIPs are (a) The Industrial Symbiosis of Kalundborg, Denmark where eight different companies (six processing companies, a waste treatment company and the municipality of the city) cooperate in financial and environmental sustainable projects; (b) The Industrial Ecosystem (INES) in Rotterdam, the Netherlands, in which members from the industrial, environmental and academic communities participate in order to stimulate the development of cleaner production; (c) The National Industrial Symbiosis Programme in the UK, which is the first industrial symbiosis project on a national scale. There are other examples such as the EIPs in Uimaharju and Harjavalta in Finland [57]. In all of these projects the companies exchange flows of mass and energy in a sustainable and economic way reducing the overall energy consumption and waste generation. However, the development of an efficient and well-structured eco-industrial park requires improving the material flow networks between participating firms [58,59]. Therefore, one of the main objectives of an EIP is the minimization of resource consumption and environmental loads by using a recycling network for raw materials, waste and energy [60]. According to this objective, the management of the material flows should meet with reduction of the use of energy resources such as fossil fuels, stimulate the use of sustainable energy as much as possible; support the balance in the process of use and production of renewable resources; and conserve renewable and non-renewable resources as long as possible in the material cycles, unless they are toxic to the environment [61]. In this regard, several works have been reported with respect to the optimization of the inter-plant material flows. First, water integration between different plants has been considered by several authors [62–72]. Regarding to energy integration, Dhole and Linnhoff [73] introduced the concept of total site energy integration between plants. Hu and Ahmad [74] proposed a total site targeting integration using the utility system; and Klemes et al. [75] incorporated fuel, power and CO_2 reductions in total sites. Marechal and Kalitventzeff [76] developed tools for energy integration between plants. Bagajewicz and Rodera [77–79] presented mathematical programming approaches for energy integration across plants. Bandyopadhyay et al. [80] incorporated total site targeting into a cogeneration process. Shenoy [81] used the unified conceptual approach developed by Agrawal and Shenoy [82] for water and hydrogen networks to find the optimal energy allocation network and thus to reduce carbon emissions. Chae et al. [60] proposed a framework to utilize waste heat from an EIP that considers four steps: Energy information collection, energy information analysis, and optimization of waste heat utilization were formulated as an MILP problem and the objective function is the minimization of the total energy cost of the target EIP, along with economic and environmental evaluation. Stijepovic and Linke [83] proposed a targeting approach for waste heat recovery across plants in industrial zones. Maes et al. [84] presented a literature review for the symbiosis of eco-industrial parks searching specific energy targets. Varbanov and Klemes [85,86] incorporated renewable energy in the total site targeting procedures. Stijepovic et al. [87] developed a targeting approach for reusing heat in industrial zones combined heat and power generation. Kralj [88] presented a simple graphical utility targeting method for heat integration between processes. Varbanov et al.