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A new graphical method for Pinch Analysis applications: Heat exchanger network retrofit and energy integration

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ABSTRACT

Energy integration is a key solution in chemical process and crude refining industries to minimise external fuel consumption and to face the impact of growing energy crises. Typical energy integration projects can reach a reduction of heating fuels and cold utilities by up to 40% compared with original designs or existing installations. Pinch Analysis is a leading tool and regarded as an efficient method to increase energy efficiency and minimise fuel flow consumptions. It is valid for both natures of design, grassroots and retrofit situations. It can practically be applied to synthesise a HEN (heat exchanger network) or modify an existing preheat train for minimum energy consumption. Heat recovery systems or HENs are networks for exchanging heat between hot and cold process sources. All heat transferred from hot process sources into cold process sinks represent the scope for energy integration. On the other hand, energies required beyond this integrated amount are to be satisfied by external utilities. Graphical representations of Pinch Analysis, such as Composite and Grand Composite Curves are very useful for grassroots designs. Nevertheless, in retrofit situation the analysis is not adequate and besides it is graphically tedious to represent existing exchangers on such graphs.

This research proposes a new graphical method for the analysis of heat recovery systems, applicable to HEN retrofit. The new graphical method is based on plotting temperatures of process hot streams versus temperatures of process cold streams. A new graph is constructed for representing existing HENs. For a given network, each existing exchanger is represented by a straight line, whose slope is proportional to the ratio of heat capacities and flows. Further, the length of each exchanger line is related to the heat flow transferred across this exchanger. This new graphical representation can easily identify exchangers across the pinch, Network Pinch, pinching matches and improper placement of fuel consumption. Furthermore, such a graph can recognise promising modifications to improve the energy performance and hence less fuel and cooling water requirement. Graphs developed in this work can be used to analyse the energy performance of existing networks with respect to energy targets. They can also be used in junction with the background process to modify basic designs or existing network for better energy integration opportunities and minimum fuel demands. The application of the new graphical method to a case study showed savings of approximately 17% in energy demands and fuel consumption.

1. Introduction

Chemical plants, including crude oil up-stream processing units are energy-intensive process industries. Among these unit operations and process equipment, distillation is found to be the most energy consuming unit. As an example, Gadalla et al. [1] reviewed the energy problems of refinery crude distillation plants as major energy intensive processes, and focused to optimise existing operating conditions for minimum energy demands. More general, Smith in his textbook [2] devoted complete chapters to introduce the fundamentals of energy consumption in distillation industry, distillation sequencing, retrofit of distillation units, optimisation of superstructure for distillation sequencing, heat integration in distillation, etc. The textbook also considered normal distillation as well as azeotropic mixtures, and presented in detail all principles and design guidelines of Pinch Analysis. On the other hand, El-Halwagi [3] considered distillation industries in many of his applications for energy integration, optimisation and sustainability. This book additionally introduced the conceptual

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design of distillation-based bio-refineries as alternative sustainable plants. Significant amounts of energy are essential for heating and cooling purposes within the process or to provide necessary heat of reactions. Typically in crude refining distillation, large amounts of fuel oil, natural gas, or in some cases part of the crude oil processed are burned in the fired heater to provide the energy required for crude fractionation. This applies to a wide range of industries, such as petrochemicals, chemicals separation, distillation industries, etc. Also, in some applications cooling is required to remove heat of reactions. Typical external utilities used for process industries are steam, hot oil, petroleum fuels, flue gases, cooling water, low-temperature cooling liquids, air, etc. Steam for heating or stripping is produced through the combustion of natural gas or crude oil fuel products. In typical process design of chemical plants, the design normally starts with the reactor, the heart of the process. Then the design proceeds to the separation task to recover un-reacted materials, leaving as much as possible pure product streams. Un-reacted materials are recycled to the reactor for more reaction opportunities, while the product is further purified to reach required market specifications. Next, the design of heat exchanger network comes into stage. In this stage, all heating and cooling requirements are provided by either heat integration or through external utilities. The last phase of design is related to the utility system, in which appropriate utilities are selected to supply the external heating and cooling demands (see Fig. 1). This hierarchical procedure is called the 'onion diagram' and is given in detail by Smith [2]. Given that distillation processes like other operations require substantial amounts of energy as hot or cold, many research efforts were put into action to identify opportunities for minimising energy consumption. Energy integration in processes is meant by recovering heat from those process streams and units that need cooling and thus through heating other streams or units which require heating. Hot streams or units are heat sources, while cold streams or units are known as heat sinks. This process is commonly known as heat integration or energy recovery. Such integration takes place in a HEN (heat exchanger network) or a preheat train. Heat is recovered from process hot sources to process heat sinks as much as possible such that energy consumption is reduced. The total energy consumption of a process is the amount of energy supplied by or the flows of external utilities in heaters or coolers. The more external utility required by the process, the more utility cost necessary for the process. Petroleum refining distillations are very typical industries with preheat trains for the processing of crude oil streams [4].

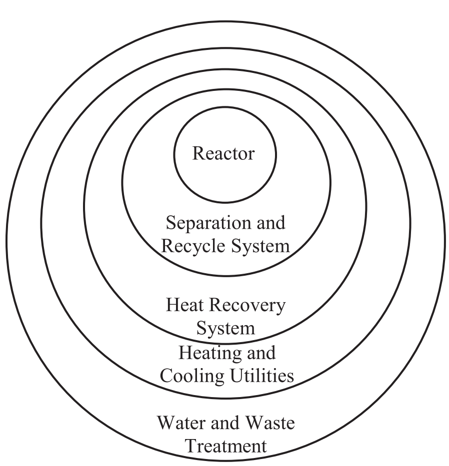

Fig. 1. Onion diagram for chemical process design [2].

Literature is rich in methods and approaches for energy integration; Pinch Analysis or Pinch Technology is one very important method among others for the efficient use of energy and other raw materials, such as water, hydrogen, etc. Most previous approaches are applied to increase energy efficiency of preheat trains used in chemical and petrochemical industries. In one of these approaches, the existing distillation unit was optimised simultaneously with the associated exchanger network to reduce energy consumption and for more capacity to be processed [5]. Shortcut models were developed within the work to model the retrofit of distillation columns. Also, in this method, the details of the existing exchanger network were considered in the optimisation algorithm through an empirical equation obtained by an extensive separate retrofit study. Other researchers focused on the distillation column as stand-alone equipment and increased its energy efficiency through an internal heat integration scheme [6]. The proposed scheme exploited the energy of the hot vapours after being compressed in heating the cold liquid of rectifying sections in an external medium, known as heat panels. These new columns are configured in a specific manner commonly called internal HIDiCs or internal heat integrated distillation columns. Asante and Zhu in their research works [7,8] developed a breakthrough approach known as Network Pinch method for retrofitting an existing exchanger networks. In this approach, the bottlenecks limiting heat recovery were first identified and then topological modifications were suggested to increase the energy recovery. Bottlenecked exchanger units in this method were termed as Pinched Matches. This last work used mathematical programming techniques in solving the retrofit problem. Based on the work of Asante and Zhu [7,8], a group of researchers extended the Network Pinch approach to revamp industrial heat exchanger networks by considering the change in the thermal properties of process streams [9]. In the latter work, structural modifications and cost optimisation were combined to minimise topology modifications. Also, Bakhtiari and Bedard [10] modified the standard Network Pinch approach by Asante and Zhu to include practical features of stream segmentation and splitting. This last work considered the advantages of varying the supply and target temperatures of streams which increased the flexibility of the work. On the other hand, Zhang et al. [11] used more recent modelling techniques and Process Integration technologies to improve the environmental performance of some existing crude distillation units. In this work, the researchers adopted the optimisation of the operating conditions to reduce the energy consumption of an industrial facility by some 8%. In a very recent work by Lluvia et al. [12], both the distillation process and the heat recovery system were optimised simultaneously to reach best results. This recent work combined models for describing distillation columns with models for the details of the existing exchanger networks to perform potential changes to each stage. Previous shortcut models [5] were extended in the work of Lluvia et al. [12] which resulted in semi-rigorous models based on stage-by-stage calculations.

Jiang et al. [13] considered retrofitting existing heat exchanger network through the selective use of heat transfer enhancement. In this work, the existing structure of the network was fixed while improving the network energy performance. A good advantage of this work was that the selective enhancement avoided the addition of new equipment or piping and engineering costs. In the same line of intensification in heat transfer, Wang and co-workers [14,15] addressed a very common problem in retrofit solutions that the conventional retrofit projects normally require significant topology modifications with more engineering complexities. This work thus developed mathematical models to solve the retrofit problem based on heat transfer enhancement. Heat transfer