Journal of Basic and Applied Engineering Research
Print ISSN: 2350-0077; Online ISSN: 2350-0255; Volume 2, Number 8; April-June, 2015 pp. 617-620
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http://www.krishisanskriti.org/jbaer.html

Heat Exchanger Network Design

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Abstract—*In context of volatility in markets and depleting traditional fuel reserves, it is the need of the hour for industries to ensure optimization of energy consumption at every stage of production. The current paper focuses on designing efficient heat exchanger networks to deliver the best results at optimal cost inputs. This includes methodologies such as pinch technology which employs heat and material balance together with integration of hot and cold streams in the network thereby minimizing the requirement for externally supplied utilities. Data extraction, analysis, designing, selection and project detailing are the key steps involved in this process simulation. Further, the network design method uses a special representation known as composite curves, which indicate the minimum energy target for the process.*

A major emphasis in the project has been laid to establish heat exchanger design networks that are easy to implement in engineering practice. Different aspects of pinch technology have been also been used in the case study. This was achieved by using basic material and energy balances for various streams of the network. There were different utilities such as hot and cold utilities which were also considered for such calculations. Using the results obtained from these calculations, the most suitable network in the given capital was determined.

Keywords: *Design, Energy, Heat Exchanger, Optimization, Pinch Technology.*

1. INTRODUCTION

Today in the industry, the design and optimization procedures are required to identify the configurations where the minimum energy consumption can be achieved. The possibilities for energy savings and the resulting environmental and economic saving for the various industrial applications can be diverse and very useful. The search for new energy resources due to the scarcity of traditional fuels and the instability in the global markets, demands that the industry maximize their efforts in the energy consumption optimization.

In process industries, during operation of any Heat Exchanger Network (HEN), the major aim is to focus on the best performance of the network. Frequently one encounter problems that degrade the HEN performance, like heat exchanger fouling, leakage in tubes, changes in process stream conditions (flow rate, temperature), frequent changes in arrangement of utility streams to optimize heat recovery in the network, shutdown of heat exchanger for maintenance, etc. Since the changes can take place in any of the heat exchangers in the network, a complete analysis of the network in an integrated method is required. In order to handle these issues a good understanding of modeling and simulation of HENs in a simultaneous approach is necessary.

The design and optimization of HENs has been extensively studied over years and significant progress has been achieved in the development of robust methods for design of cost-optimal networks. The objective of this project is to develop HEN models for design, monitoring and optimization that are easy to implement in engineering practice for a particular case study.

2. PINCH TECHNOLOGY

Pinch Technology provides a systematic methodology for energy saving in processes and total sites. The methodology is based on thermodynamic principles. A Pinch Analysis starts with the heat and material balance for the process. Using Pinch Technology, it is possible to identify appropriate changes in the core process conditions that can have an impact on energy savings. After the heat and material balance is established, targets for energy saving can be set prior to the design of the HEN. The Pinch Design Method ensures that these targets are achieved during the network design. Targets can also be set for the utility loads at various levels (e.g. steam and refrigeration levels). The utility levels supplied to the process may be a part of a centralized site-wide utility system (e.g. site steam system). Pinch Technology extends to the site level, where in appropriate loads on the various steam mains can be identified in order to minimize the site wide energy consumption. Pinch Technology therefore provides a consistent methodology for energy saving, from the basic heat and material balance to the total site utility system.

The principal objective of this technology is to match hot and cold streams with a network of exchangers so that demand for externally supplied utilities is minimized. Pinch technology establishes temperature difference, designated as the pinch point, which separates the overall operating temperature region observed in the process into two temperature regions. Once a pinch point has been established, heat from external sources must be supplied to the process only at temperature above the pinch and removed from the process by cooling media at temperature below the pinch. Such a methodology will maximize the heat recovery in the process with the establishment of a HEN based on pinch analysis principles. The best design for an energy efficient HEN will result in a trade-off between the energy recovered and the capital cost involved in this energy recovery.

The network temperature pinch represents a bottle neck to feasible heat recovery in HEN design. The pinch design method can be used to identify the best starting value of ΔTmin. ΔTmin is used to correspond to a minimum energy solution. The pinch design method also involves a controlled reduction in the number of "units" (i.e. process and utility exchangers) this may require "backing-off" from the minimum utility usage. In addition, the pinch design method identifies situations where stream splitting is inevitable for a minimum utility design.

3. LITERATURE REVIEW

Heat exchanger design can be a complex task and advanced optimization tools are useful to identify the best and cheapest heat exchanger for specific duty. Linnhoff, 1983 [1] presented a novel method for the design of HENs. The method is the first to combine simplicity to be used by hand with near certainty to identify "best" designs even for large problems. "Best" designs feature the highest degree of energy recovery possible with a given number of capital items. Moreover, they feature network patterns required for good controllability, plant layout, intrinsic safety, etc.

Pinch Analysis starts with the heat and material balance for the process [2]. Using Pinch Technology, it is possible to identify appropriate changes in the core process conditions that can have an impact on energy savings. After the heat and material balance is established, targets for energy saving can be set prior to the design of the HEN. The Pinch Design Method ensures that these targets are achieved during the network design. In process industries, HENs represent an important part of the plant structure. The purpose of the networks is to maximize heat recovery, thereby lowering the overall plant costs. Previously published research on HENs deals with two categories:

- Synthesis of HENs with the goal of designing a structure that provides the lowest cost.
- Data reconciliation with establishing true performance of the network and identifying correct heat transfer coefficients for individual exchangers in the network [3].

Suraya et. al, 2013 [4], presents the application of the proposed model-based methodology in solving integrated process design and control (IPDC) of HENs. Many methods for HENs synthesis have been developed over the past decades, which aim to provide HENs designs that yield a reasonable trade-off between capital and operating costs. Energy conservation is important in process design. In industrial experience, the calculation of the minimum heating and cooling requirements reveal significant energy savings [5]. Specifically, Imperial Chemical Industries in the United Kingdom and Union Carbide in the United States have both stated the results of numerous case studies that indicate 30% to 50% energy savings compared to traditional practice.

4. HEN DESIGN METHODOLOGY

Fig. 1 provides an overview of key steps in pinch technology.

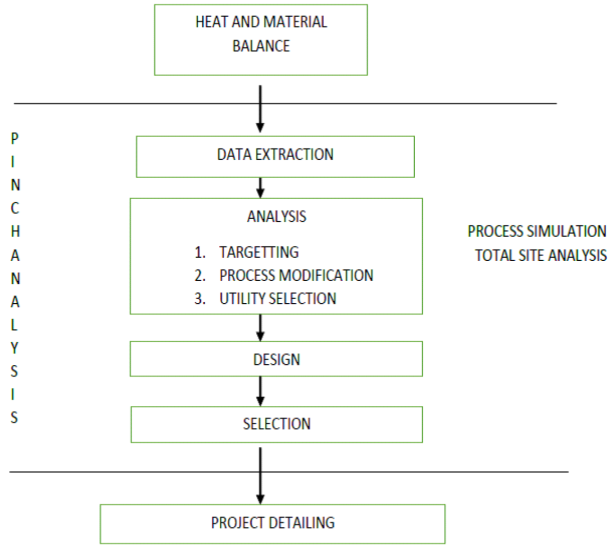

Fig. 1: Overview of key steps in Pinch Technology

The first two steps are data extraction and analysis. Data extraction involves translation of flow-sheet information into relevant thermal and cost information required for the application of pinch technology. The second step is pinch analysis based on targets. This involves targeting for energy, trade-offs in targeting mode between capital and energy, targeting for process modifications and targeting for multiple utility levels and placement of heat engines and heat pumps [6]. The method designs a network that achieves the energy targets within practical limits. The network design procedure uses a special representation for HENs called the "Grid Diagram".

The proposed HEN synthesis methodology is applied to one case study. The results of the current approach are compared with the results earlier published in terms of the network structure, global cost of the networks, and area of the heat exchangers.

5. CASE STUDY

The following process flow sheet was taken up as a case study for HEN synthesis [7].

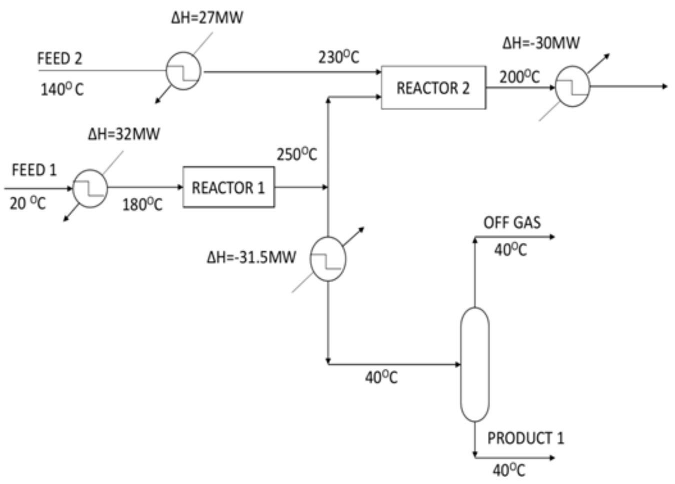

Fig. 2: Flow sheet for case study

Several hot streams and cold streams are shown in the flow sheet (Fig.2). Flow rates, temperature and heat duties for each stream are shown. Heat capacities are assumed to be constant. Heat capacity flow rates are calculated for every stream and are shown in Table1.

Table 1: Process flow thermal data

Stream	Type	Heat Capacity Flow Rate	Film Heat Transfer Coefficient MW/m2.K
Reactor 1 feed	Cold	0.2	0.0006
Reactor 1 product	Hot	0.15	0.0010
Reactor 2 feed	Cold	0.3	0.008
Reactor 2 product	Hot	0.25	0.008

4.1 Composite Curves and Energy Targets

Composite curve shows the two hot streams individually on temperature-enthalpy axes. If heat capacities are constant, then changes will occur only when streams start or finish. Fig. 3 shows the composite curves for hot and cold process.

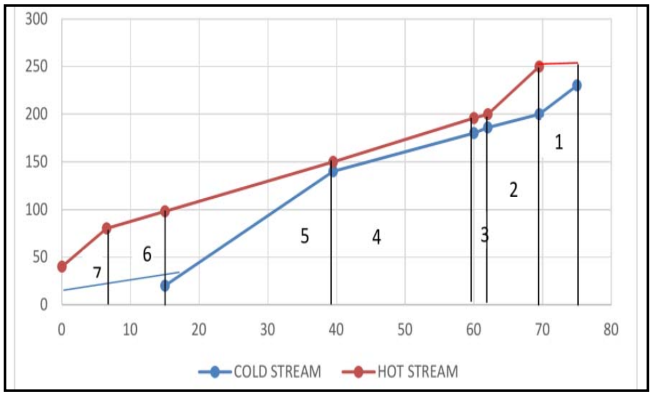

Fig. 3: Balanced composite curve

Within each temperature range, the streams are combined to produce a hot composite stream. In any temperature range, the enthalpy change of the composite stream is the sum of enthalpy change of the individual streams.

Where curves overlap (see Fig. 3), heat can be recovered vertically from the hot streams. The way in which the composite curves are constructed allows maximum overlap between the hot and cold streams. Maximizing the energy recovery minimizes the external requirements for heating and cooling duties and minimizes the external requirements for heating and cooling. Where the cold composite curve extends beyond the start of hot composite curve, heat recovery is not possible, and the cold composite must be supplied with external hot utility like steam. This represents the target for hot utility and for end of hot section, cold utility like water is provided. This is used to construct balanced composite curve.

The composite curve is set to have a minimum temperature of 10°C as per the process requirement. Table 2 gives the results from the composite curve shown in Fig. 3.

Table 2: Result from composite curve

Minimum cooling utility	15 KW
Minimum heating utility	5.5 KW
Pinch point temperature	Hot – 150oC, Cold - 140oC

4.2 Grid Diagram

Fig. 4 shows an alternative representation of the flow sheet known as the grid diagram. The grid diagram shows heat transfer operation only. A heat exchange match is represented by a vertical line joining two circles on the two streams being matched. An exchanger using hot utility is presented by a circle with an "H". An exchanger using cold utility is presented by a circle with a "C".

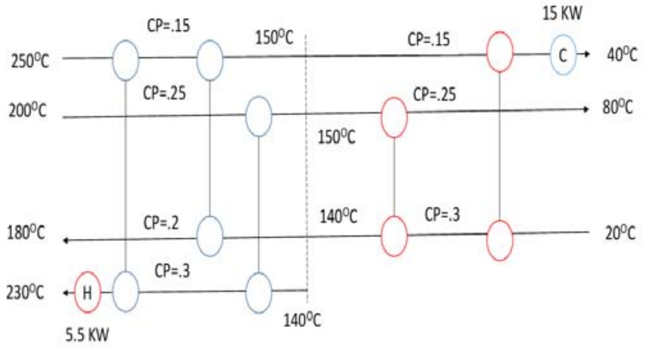

Fig. 4: Grid diagram

Tick-off Heuristic

Once the matches have been chosen to satisfy the criterion for minimum energy the design is continued to keep capital cost to a minimum. One important criterion to minimize capital cost is to keep the number of units to a minimum by using tick–off heuristic [8]. For our study minimum number of units is calculated as follows-

$$N_{UNITS} = (S\text{-}1)_{\text{Above Pinch}} + (S\text{-}1)_{\text{Below Pinch}} = 7$$

Area Target

The composite curves make it possible to determine the energy targets for a given value of ΔT_{min}. The composite curves can also be used to determine the minimum heat transfer area required, A_{min}, to achieve the energy targets [9]. Table 3 gives the estimated heat exchanger areas.

$$\mathbf{A_{MIN} = \Sigma_i[1/\Delta T_{MIN}\, \Sigma_j q_i/h_j]}$$

where: i is i_{th} enthalpy interval

j is j_{th}stream

ΔT_{LM} is log mean temperature difference

q_j is enthalpy change of j_{th} stream

h_j is heat transfer coefficient of j_{th} stream

4.3 Utility and Area Costs

Utility and material cost is the major part of the capital cost target and total cost target [10]. The cost of utility and heat exchanger material cost was calculated after the area of heat exchanger was calculated assuming carbon steel as the material of construction. The estimated capital cost of exchanger was approximately $123200 (Rs.134 Lakhs).

Table 3: Heat exchanger areas

No.	ΔTLM	HOT STREAM Σ(Q/H)	COLD STREAM Σ(Q/H)	AREA (m2)
1	15.66	2000	7500	606.64
2	37.11	7000	8750	424.44
3	4.93	2500	2500	1014.2
4	41.96	26250	3500	1460
5	74.76	28125	37500	877.8
6	12.98	12500	16669	2247.07
7	25.96	6500	6500	500.77
Total Area				7130.92

For estimating the total cost, network capital cost was also calculated. This was obtained by assuming that the number of shells is greater than the number of units.

$$\mathbf{N_{SHELLS} \geq N_{UNITS}}$$

$$\text{Network capital cost} = N\,[a+b\,(A_{NETWORK}/N)^{C}] = \$2435000 \text{ (Rs. 146 Lakhs)}$$

If steam and cooling water are used as utility, then assuming standard rates for the same, the total utility costs can be estimated. In the above case study, the steam and cooling water cost assumed was 120,000 $/MW.yr and 10,000 $/MW.yr.

Total utilities cost = steam cost× Steam consumption + cooling water cost× Cooling water consumption.

Based on above case study, the total utility cost is estimated to be 810,000 $/yr. Table 4 summarizes the results for the case study.

Table 4: Case study results

Heat exchanger area	~ 7130 m2
Installed capital cost	~ 123,200 $
Number of units	7
Network capital cost	~ 243500 $
Total utility cost	~ 810,000 $/yr

6. CONCLUSIONS

HEN design can be a complex task, and advanced optimization tools are useful to identify the best and cheapest HEN for a specific duty. In this project, a method of the HEN design and its optimization problem was used based on Pinch Technology as its basis for design. Based on this method, composite curves for various hot and cold streams were drawn. The Pinch Point was determined from these combined curves. HEN designing starts at the pinch point.

For the present project, the heat exchanger area estimated was 7130 m^2 and number of units was 7. Also, network capital costs and installed capital costs along with total utility costs were estimated based on reference utility costs.

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