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APPLICATION OF MODIFIED PINCH TECHNIQUE IN THE OPTIMIZATION OF TOTAL ANNUAL COST OF HEAT EXCHANGER NETWORKS

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Abstract

This research study was aimed at optimizing the total annual cost (TAC) of heat exchanger network (HEN) related problems using modified pinch technique on a software that blends pinch technique with mathematical programming. In this research study, modified pinch technique contained in the Aspen Energy Analyzer software package was utilized and applied in the designing, targeting and optimization of the networks for the minimum TAC for the two cases extracted from literature and solved. The results obtained for total annual cost on the two cases (cases 1 and 2) were $220.541/yr and $567,383/yr respectively which were the least TAC in comparison with the solution of other researchers that used methods involving mathematical programming. The results obtained in this study and the general comparison show that modified pinch technique as embedded in Aspen software can be used to simulate and optimize HENs yielding a TAC comparable or even lower than others obtained by previous researchers that used pure mathematical modeling.

Keywords: *Optimization, Pinch Analysis, Super Targeting, Total Annual Cost, Integration*

1. Introduction

The increasing energy demand in recent years has heightened the quest for successful and cost-effective investment into energy integration and conservation. Instability in the prices of fuels and the need for compliance with ecological standards has also necessitated greater efficiency in energy usage. Following these needs, energy conservation has become the prime interest of many process industries, compelling them to search for possible ways of optimizing energy consumption in their operations (Furman and Sahinidis, 2002).

Consequently, one of the most reoccurring challenges in process industries is the energy consumption for production processes (Robin, 2009). It accounts for one of the highest contributions to the total cost of industrial products. Most industrial processes require the consumption of energy at certain temperature value and disposal at another level, as there are streams in need of heating and some other ones in need of cooling;

this can be achieved using hot and cold utilities respectively. The heating and cooling processes occurs in heat transfer equipment such as heat exchangers, boilers, coolers etc (Woranee, 2009).

In energy integration, the aim is to maximize process to process heat recovery and minimize the use of external utilities (Krishna and Murty, 2008; Azeez et al. 2012). To improve the performance of an existing process, modification of the process can be done to reduce energy consumption and subsequently, the total annual cost (TAC) through the use of energy integration. This can be in form of application of pinch technology or heat exchanger networks (HENs) design (Azeez et al. 2012; Hallale, 1998; Akande, 2007). However, the integration of these operations to achieve an overall optimum process flow sheet is yet to be fully recognized (Woranee, 2009).

HENs can be designed either through simultaneous or sequential synthesis techniques with the goal of obtaining the minimum HEN structure for a process to achieve minimum investments and operating costs. The sequential synthesis technique separates the HENs problem into a multiple of sub-problems to minimize the complexity and computational criteria of the problem. The sub-problem includes the minimum utility usage (Qc_{min} and Qh_{min}), the minimum number of units (U_{min}) and the minimum area of the network (A) which are then solved consecutively (Gundersen et al., 1997). A typical example of this technique used in the optimization of the TAC is the pinch analysis (Linnhoff, 1993).

The simultaneous synthesis technique, which is mathematical in nature, involves determining the optimal HEN at a single step. In evaluating the multiple trade-offs on the HENs problem, all the factors are assessed all at once (Yee and Grossmann, 1990; Krishna and Murty, 2008; Azeez et al. 2012). A typical example of simultaneous technique that have been utilized for the optimization of the TAC and in designing of HENs includes Stage-Wise Superstructure (SWS) of Yee and Grossmann (1990), in which the number of stages in the superstructure is obtained by the number of hot and cold streams in the process. Another one is the Interval Based Mixed Integer Non-linear Programming (MINLP) superstructure IBMS of Isafiade and Fraser (2008), which utilizes the supply and target temperature of one set of stream (hot or cold) to divide the superstructure into intervals. There is also Supply and Target Based Superstructure (S&TBS) of Azeez *et al.*, (2012) in which the supply temperatures of hot streams and target temperatures of cold streams are used to define the superstructures interval. In the same study, target of hot streams and supply cold streams were used to define intervals and such superstructure was named (T&SBS.)

The mathematical techniques as applied by different techniques mostly derived their basis from the traditional pinch technology. Pinch technology is a sequential methodology based on thermodynamic concepts and principles that can be used to design process plants with reduced energy and sometimes capital costs. It is to ascertain efficiency and provide potential design configurations that can improve performance. It alsomaps out the flow of energy within a system and to identify the possible routes of maximizing heat recovery through efficient way and to minimize the necessity for external utilities. Thus, giving an insight to be used in determining energy saving processes with a process or utility stream, with an overall system view that ensures process compatibility and completeness by setting the minimum consumption for the process (Shenoy, 1995).

One of the fundamental strength of pinch analysis is that it determines the most appropriate set of heat exchange stream matches, and thus determine the minimum requirement for both hot and cold utilities in a process (Kemp, 2007). Process systems have in the past been designed using this traditional design techniques, which involved energy balances, rules of thumb or heuristics, good engineering judgment and creative ability of the designer.

The calculations obtainable in pinch technology are conceptually simple and can mostly be done without any machine. However, in large-scale problems, they can become cumbersome and time consuming. Thus, the availability of computer software such as General Algebraic Modeling systems as used by some researchers and Aspen Energy Analyzer used in this work as made available in Aspen (2018).This energy analyzercombines the traditional method of pinch methodology with mathematical programming for effective HEN design result (Azeez et al., 2019). It has been used in HENs optimization by various researchers and will be employed in the investigation of TAC of some networks whose results will be compared with those of other available studies.

2. Aspen Energy Analyzer

This is a simulation software package developed and outlined by AspenTech for energyintegration. It can be used for performing optimal heat exchanger network design to minimize process energy usage. It can as well be used by the designer to check the feasibility of a process, study and investigate the effect of various operating parameters on various processes (Hsie and McAvoy, 1990). It offers a high degree of flexibility as there are multiple ways to accomplish specific tasks using the software. This flexibility combined with a consistent and logical approach to the deliverable capabilities make Aspen Energy Analyzer an extremely adaptable process simulation tool. It is a combination of pinch technique (sequential) and mathematical (simultaneous) programming software package (AspenTech, 2008).

In the design of HENs, Aspen Energy Analyzer incorporates concepts of pinch analysis as described in Linnhoff (1993) such as; the determination of the pinch point, pinch temperatures, and energy targets are obtained from the compositecurves (hot and cold). The grand composite curve (GCC) is used to ascertain the choice of utilities and the temperature requirements as with the traditional pinch technique. The heat recovery approach temperature (HRAT) /optimum temperature difference ΔT_{min}, for minimum cost using energy capital trade off is determined from the super-targeting curve (range targets in Aspen Energy analyzer) and the design of the network is performed on the grid diagram which shows the flow of streams and recovery matches as made obvious in the traditional pinch technique such as in Linnhoff and Ahmad (1989).

Evaluation of targets which signify values recommended for design of optimal networks in ideal situation such as energy targets, utility targets, heat exchanger area targets, number of exchanger units target, number of shells targets, operating cost targets, total annual cost targets, and capital costs targets are performed using the composite curves, the balanced composite curves, log mean temperature difference (LMTD), bath formula and cost functions embedded in the software which are also derived from the traditional pinch technique (Linnhoff and Ahmad, 1989; Linnhoff, 1993; Shenoy, 1995) The design of the HEN on the grid diagram using Aspen Energy Analyzer can be accomplished either manually by the designer, in which the designer is in full control of his design using insights and judgment in the design process as far as possible while also following the rules of pinch in the HEN design or in the alternative, use of the Automatic Recommend Design (ARD) feature of the software which is dependent on the specified process streams, utility and economic data. The ARD feature of the software is comprised of a linear programming model and mixed integer linear programming model which simultaneously optimize the heat exchanger area, number of units and heat load for each utility (AspenTech, 2008).

An important feature of the Aspen Energy Analyzer is the ability of the software to optimize already completed designs. This is carried out using heat exchanger loads and split flow ratio as optimization variables for the objective function which could be minimization of TAC or minimization of area of heat exchanger. This is subject to the aim of designing the HEN by the designer which can be achieved by the optimization tool of the software. In performing the optimization using the optimization tool of the software, it takes into account the lack of infeasible heat exchangers, untied streams, number of degrees of freedom, exchanger inlet and outlet temperatures that have be specified prior to design and leaves it fixed during the optimization process (AspenTech, 2008).

3. Problem Statement

In most process industries, the rate and demand of energy utilization between streams and processes cannot be over emphasized as a lot of energy is been consumed in these processes. In a process plant, there are numbers of process streams (hot and cold to be cooled and heated respectively). It is therefore necessary to synthesize a heat exchanger network that is cost effective which can exchange heat from the hot streams to the cold streams so as to achieve a minimum total annual cost network.

The information needed on the process: heat capacity flow-rates, inlet and exit temperatures and the heat transfer coefficients of each process stream. Also available for use are heating and cooling utilities whose cost, inlet temperatures, exit temperatures and the heat transfer coefficients are also given, along with heat exchanger cost and annual capital cost.

4. Methodology

The heat integration software utilized for this research paper is Aspen Energy Analyzer V8.8 and the simulation procedure is as shown in Figure 1. The procedure for the HEN process involves data extraction from previous works, input of process stream, utility stream and economic data, simulation of the process to obtain plots of composites curves, grand composite curves, balanced composite curves as well as other integration curves, plotting of super targeting curve to obtain the optimum ΔT_{min}, targeting (energy, units, area and cost targets). Having known the targets, the design of the HEN is then performed either manually or automatically (using the ARD feature of the Aspen Energy Analyzer) on the grid diagram interface of the software, the designed HEN is then optimized for minimum TAC using the optimization tool feature of the software. The optimized TAC of the designed HEN was then compared to the TAC of previous researcher for the same HEN problem solved.

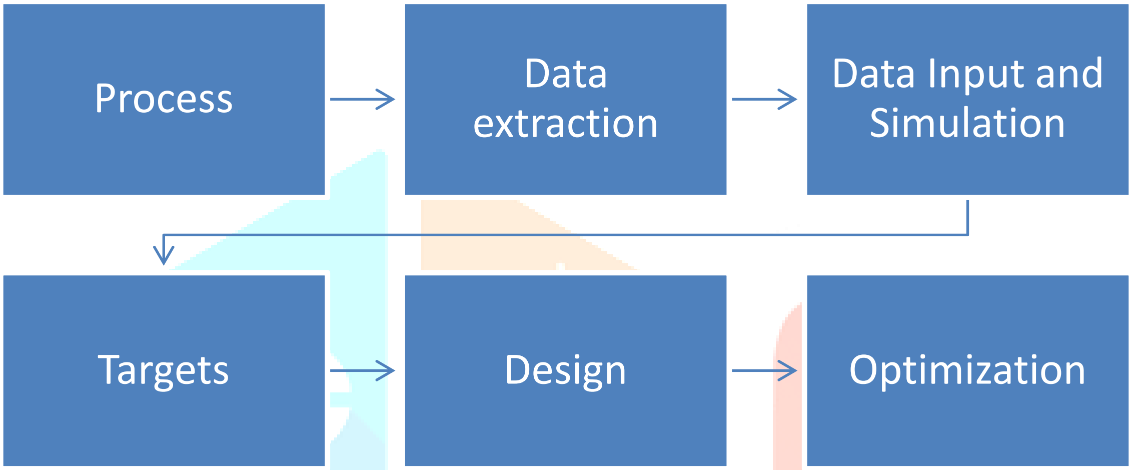

Figure 1: Block flow diagram of procedure involved in HEN design.

5. Results and Discussion

5.1 Example 1

This is a four stream Problem extracted from Isafiade and Fraser (2008). It involves two hot streams and two cold streams. It also includes one hot and one cold utility which are steam and cooling water respectively. The stream and capital cost data for these two streams are shown in Table 1. The minimum allowable temperature difference ΔT_{min} for this network was obtained from the super-targeting to be 13°C and used in designing the network. The designed network for this problem consists of seven heat exchanger units and a split stream of equal temperatures values (isothermal), heat exchange area of 2609.00 m^2 and a TAC of $220,541/year as shown in Figure 2. The hot utility usage is 300 kW while the cold utility usage is 220 kW. Table 2 compares the TAC of this work to those of previous researchers

Table 1 : Cost and stream data for Example 1

Stream	**T^{supply} (°C)**	**T^{target} (°C)**	**F (kW C^{-1})**	***h* (kWK^{-1}m^{-2})**	**Cost($kW^{-1}yr^{-1})**
H1	175	45	10	0.2	-
H2	125	65	40	0.2	-
C1	20	155	20	0.2	-
C2	40	112	15	0.2	-
S1	180	179	-	0.2	120
W1	15	25	-	0.2	10

Annual capital cost for heat exchangers = 30,000 + 750 [Area(m^2)]0.81
Annualization factor = 0.322

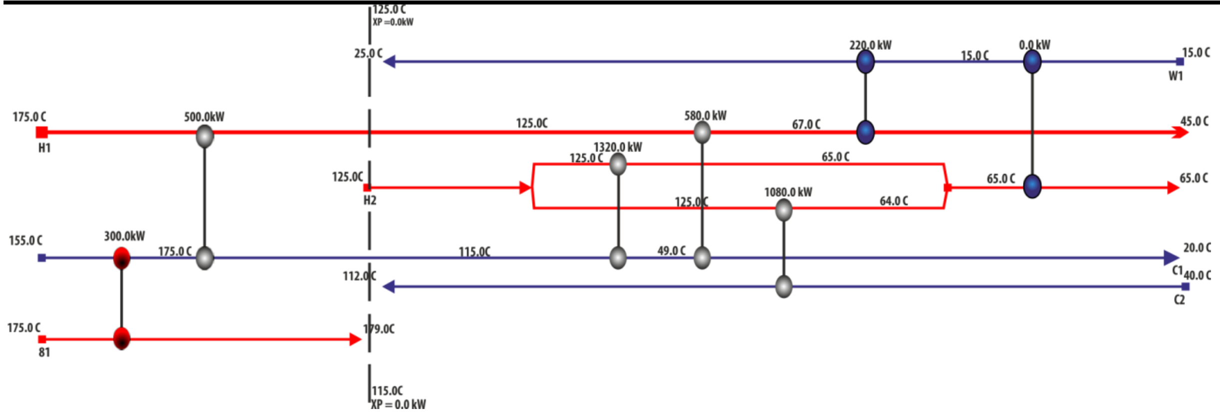

Figure 2: Heat Exchanger Network designed for Example 1

Table 2: Comparison of results for Example 1

Method	**Split Stream**	**No of Units**	**TAC ($/year)**	**Area (m^2)**	**Difference %**
T&SBS of Azeez et al.	3	6	240,253	--	8.20
Cold stream based IBMS	3	6	239,332	--	7.85
Hot stream based IBMS	2	6	237,800	--	7.25
S&TBS (type 1)	2	6	235,781	--	6.46
S&TBS (type 2)	2	6	235,781	--	6.46
Simplified SWS	2	6	235,400	--	6.31
This work	1	7	220,541	2609.00	0.00

5.2 Example 2

This problem was extracted from Isafiade and Fraser (2008) which involves five hot streams and one cold stream, the utilities used are steam and cooling water. The stream and cost data for these streams are shown in Table 3. The minimum optimum temperature difference ΔT_{min} from the super targeting curve was obtained to be 10^0K and used in the designing the network. The network designed consists of nine (9) exchanger units and one splits of the cold stream (C1), heat exchange area of 505.20 m^2 and TAC of $567,383/year as shown in Figure 3. The hot and cold utility usage is 3620 kW and 160 kW respectively. Table 4 compares the TAC of this work to those of previous researchers

Table 3: Cost and stream data for Example 2

Stream	**T^{supply} (K)**	**T^{target} (K)**	***F* (kW/ K)**	**Cost($/kWyr)**
H1	500.00	320.00	6.00	-
H2	480.00	380.00	4.00	-
H3	460.00	360.00	6.00	-
H4	380.00	360.00	2.00	-
H5	380.00	320.00	12.00	-
C1	290.00	660.00	18.00	-
S1	700.00	700.00	-	140.00
W1	300.00	320.00	-	10.00

The overall heat transfer coefficient, (U) = 1.00 (kW/mK) for all matches.
Annualized cost = 1200.00[Area (m^2)]$^{0.006}$ for all exchangers utility cost in $/kW yr

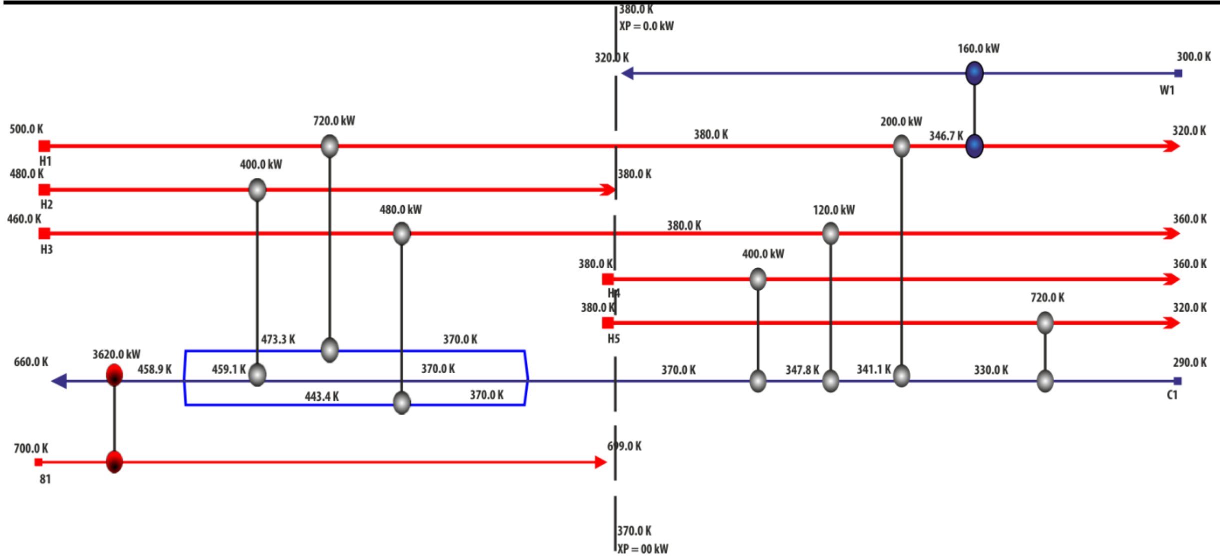

Figure 3: Heat Exchanger Network designed for example 2

Table 4: Comparison results for example 2

Method	Split Stream	No of Units	TAC ($/year)	Area (m^2)	Difference %
IBMS of Isafiade and Fraser (2000)	1	7	581,942	___	2.50
SWS of Yee and Grossman (1900)	1	7	576,640	___	1.60
This Present work	1	9	567,383	502.20	0.00

6. Conclusion

This research work studied the application of Aspen Energy Analyzer, a modified pinch software package that has linear programming model embedded in the solver. It was used to simulate and optimize the total annual cost (TAC) of heat exchanger networks (HENs). From the results of the simulation and optimization of the HENS related problem performed using Aspen Energy Analyzer; the following conclusions can be deduced:

1. Analysis of the results in the two cases solved depicts that a modified pinch technology can be used in determining the TAC of HENs that can be compared with those of previous researchers.
2. The results of the two cases solved showed that modified pinch technique using Aspen Energy Analyzer is capable of giving a lower TAC compared to the result of previous researcher that used superstructures (traditional pinch analysis).

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