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ANALYSIS OF HEAT EXCHANGER NETWORKS FOR MINIMUM TOTAL ANNUAL COST (TAC) USING PINCH ANALYSIS

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ABSTRACT
This study presents pinch analysis of some heat exchanger networks (HENs) problems using Hint integration software to analyzer heat exchanger networks (HENs) problems. Three problem examples reported to have been solved using different approaches by various researchers to obtain the least possible total annual cost (TAC) was solved using HINT software and the result obtained is presented. It shows that this approach was the best in solving problem example 2 and 3 type and second best for problem example 1.However,it was observed in this study that reduction in piping cost in the absence of split does not necessarily translate into the lowest TAC. The overall assessments of the various approach to solve these problems shows that HINT has proven to be the best in handling different kind of heat exchanger network problem aimed at minimizing total annual cost.

Keywords:HENS, TAC, HINT, networks, integration.

1. INTRODUCTION

Energy integration offers a novel approach that reduce energy consumption and total annual cost where the existing system required modification to improve performance (Akande, 2007). Energy is needed to drive the heat exchangers system in the process line, where a set of hot process streams to be cooled and a set of cold streams to be heated. This call for the energy integration in the form of heat exchanger networks (HENS) design. In process integration, the external heating and cooling utilities are reduced to save energy and total annual cost (TAC) (Smith, 1995). The optimization of chemical processes in industries is being given serious attention because of the need to reduce energy consumption in the face of increasing energy cost. This will ultimately lead to reduction in production costs, improved product quality, meeting safety requirements, reduction in energy consumption, and compliance with environmental regulations. The main objective is often economics and is stated in various terms such as return, profitability or payback period of an investment (Smith, 2005).

Pinch analysis begins and has now advanced to solve problems in engineering where heating and cooling of process materials required effluent quality, improvement in product yield, debottlenecking, and safety of the process. The concept of pinch analysis evolved over the years as a result of various research efforts made by a substantial number of researchers. The general progress that has been made over the years to accomplish energy minimization in HENs and also to develop an optimal heat exchanger network design using pinch analysis have been presented in literature (Hohmann, 1971; Linnhoff and Flower, 1978; Linnhoff *et al.*, 1982). Specific researchers that have adopted mathematical techniques include Yee and Grossman (1990), Isafiade and Fraser (2008), Azeez, *et al.* (2012) and Azeez, *et al.* (2013). Lawler and wood (1966) optimized energy exchange to obtain a network design of minimum cost without putting stream split into consideration. The use of modified pinch analyzer (Hint software) is hereby investigated to optimize TAC for problems that have been solved by other researchers as presented in the three examples in this paper.

2.0METHODOLOGY

2.1.1 Materials

Data extraction: The materials used include previous research journals for data extraction.

Soft wares: The software used is HINT

Computer System: HP 620, 64 bit operating system, 2G RAM, 2.3 GHz processor, Window 7 operating system.

2.1.2Methodology

The methodology of this research work consist of data extraction from literature, data input and simulation in HINT; Design of Grid Diagram in simulation environment; Optimization of ΔTmin in HINT and finally comparison of the results obtained using the packages as summarized in Figure 1.

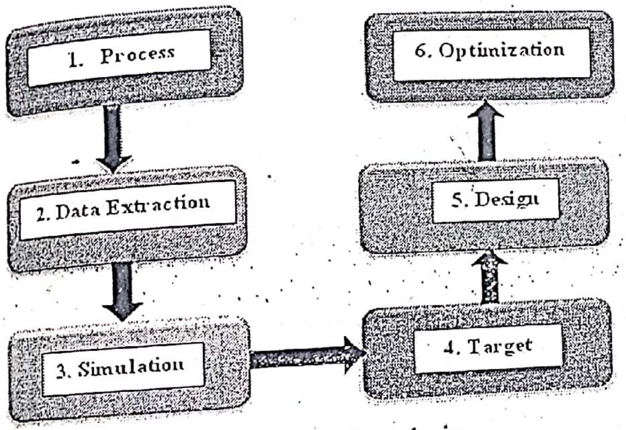

Figure 1 Phases involved in Pinch analysis

Data input and simulation in HINT

The data obtained from the work of previous researchers were used as input to the simulation environment of HINT (indicated as add stream dialogue box) from which composite and grand composite curves are generated as well as the grid diagram with the assumption of ΔTmin in the menu bar.

Design of Grid Diagram in HINT

The matching and splitting of the streams was carried out on the grid through the following procedures: the matching was carried out using MCp rule that said above the pinch the number of hot streams ≤ Number of cold streams and MCp of hot streams ≤ MCp of cold streams. The second rule emphasized that below the pinch the number of hot streams ≥ Number of cold streams while MCp of hot streams ≥ MCp of cold streams. Stream split was carried out where the MCp rule is violated. The utility heater and cooler were placed after all possible matching was achieved at points where heating and cooling are required respectively. The matching which has various options above and below the pinch was verified using remaining problem analysis (RPA)to obtain the best possible total heat flow area close to the area target after all exchangers above and below the pinch is installed. ThoughRPA analysis can be based on energy and capital cost other than target area selected in this work. After the RPA based on target area, the energy target, minimum number of units and cost target was evaluated and displayed for the optimal minimal area selected.

Optimization of ΔTmin in HINT

The result of the total minimum cost was optimized using optimal ΔTmin. The ΔTmin for energy targets was selected for optimization in the diagram menu ΔTmin analysis. The optimal ΔTmin can be identified on the cost target versus ΔTmin graphs plotted in HINT.

3. RESULTS AND DISCUSSIONS

Examples

In all the three examples presented, RPA based HINT package approach was used in the modelling of heat exchanger networks with objective function of minimum total annual cost optimization.

Example1: Linnhoff *et al.* (1982)

This example was previously reported in the work of Linnhoff *et al.* (1982). It consists of two hot streams, two cold streams, along with steam and cooling water as utilities. The Stream and cost data are as shown in Table 1. The Linnhoff *et al.* (1982) solution to this problem using pinch analysis was followed by other approaches including mathematical approaches (Yee and Grossmann, 1990; Grossmann, 1985; Azeezet *al.*, 2012). Table 2 shows the result obtained for this example using HINT-RPA package to solve this problem and comparison of the result with those of previous researchers has been made with the grid diagram presented in Figure 2. The optimal minimum TAC of $ 83,107/year obtained in this work was the least after Stage wise superstructure (SWS) of Yee and Grossmann (1990) with percentage difference of 3.53 % from the least TAC. This significant improvement obtained can be linked to the use of the remaining problem analysis (RPA) for best stream matches that were not considered in the work of Linnhoff *et al.* (1982) pinch analysis. The number of heat exchanger unit obtained is five (5) which was the least obtained in the previous research works. This shows that the pinch technique is able to simultaneously minimize the competing costs in HEN. The absence of split in the solution obtained using HINT-RPA is another added advantage of making piping easier. It should be noted that Yee and Grossmann (1990) approach that resulted into best TAC used DICOPT++ in GAMS which is non-linear optimization step.

Table 1: Stream and Cost Data for Example 1 Linnhoff *et al.* (1982)

Stream	Ts (K)	Tt (K)	F (kW K^{-1})	Cost ($ kW^{-1} $year^{-1}$)
H1	443	333	30	-
H2	423	303	15	-
C1	293	408	20	-
C2	353	413	40	-
S1	450	450	-	80
W1	293	313	-	20

U = 0.8 kW m^{-2} K^{-1} for all matches without steam. U = 1.2 kW m^{-2} K^{-1} for matches with steam. Heat exchanger annual cost = $1000 (A) $^{0.6}$ (A in m^2).

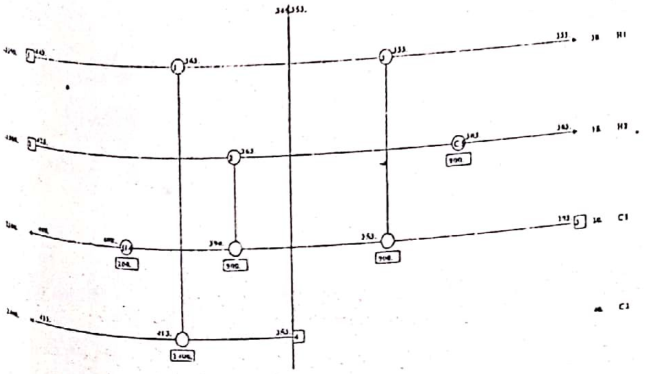

Fig.2: Grid Diagram for Example 1

Table 2: Comparison of Results for Example 1

Method	Stream splits	No. of units	TAC ($/year)	Difference (%)
Supply & target based superstructure (S&TBS) (Type 1) Azeez et al. 2012	1	5	93,391	16.34
Supply & target based superstructure S&TBS (Type 2) Azeez et al. 2012	1	5	90,672	12.95
Supply based superstructure (SBS) of Azeezet *al.* 2013	2	7	90,521	12.77
Magnets Solution of Grossman (1985)	-	6	89,832	11.91
Pinch technique of Linnhoff *et al.* (1982)	-	7	89,832	11.91
Target & Supply based superstructure (T&SBS)	2	6	87,611	9.14
Pinch technique (HINT), present study	0	5	83,107	3.53
Stage wise superstructure (SWS) of Yee and Grossmann (1990)	2	5	80,274	0.00

Example 2 Yee and Grossmann (1990)

This problem was previously reported in Magnet user Manual and Yee and Grossmann (1990) adopted it for analysis using SWS method capable of handling cases requiring stream splits. The problem consists of five hot streams, one large cold stream, one hot utility (steam) and cold utility (cooling water). The stream and cost data are shown in Table 3 and Figure 3 shows the grid diagram obtained in this work. The problem was analysed by many researchers with high expectation of having as much number of splits as possible as demonstrated by the results obtained as contained in Table 4. Previous attempt to minimize the total annual cost with least number of split in this problem was carried out by many researchers (Yee and Grossman, 1990; Isafiade and fraser, 2008a; Azeezet *al.*, submitted for publication; Azeezet *al.*, 20012) with the expectation of many splits. The application of RPA based HINT technique to evaluate this problem resulted into two stream splits as reported to have been obtained in previous work (GA of Lewin, 1998). The number of units obtained is 8 slightly lower than that of GA of Lewin (1998). This number of splits is the highest maximum obtained in all previous work with unit number close to the average obtainable as shown in Table 4. The approach used in this work resulted into the least total annual cost (TAC) of $ 562,331/year when compared with the least obtained by Azeez*et al.* (2013) with 1.19 % difference. Comparison has shown that the objective function of minimum total annual was achieved in this work and the potentials of remaining problem analysis as a rebust optimization tool in this type of pinch has been revealed. The use of pinch without RPA by Linnhoff *et al.* (1982) resulted into 11.91 % higher total annual costs. This variation and improvement in RPA base HINT can be linked to its ability to select the best match among all the available possibilities that can give the least optimal minimum area compute by the area target.

Table 3:Streams and Cost Data for Example2.

Stream	Ts (K)	Tt (K)	F (kW K^{-1})	Cost ($ kW^{-1} year^{-1})
H1	500	320	6	-
H2	480	380	4	-
H3	460	360	6	-
H4	380	360	20	-
H5	380	320	12	-
C1	290	660	18	-
S1	700	700	-	140
W1	300	320	-	10

U (kW m^{-2} K^{-1}) = 1 for all matches, heat exchanger annual cost =$1200(A)$^{0.6}$ for all exchangers (A in m^2).

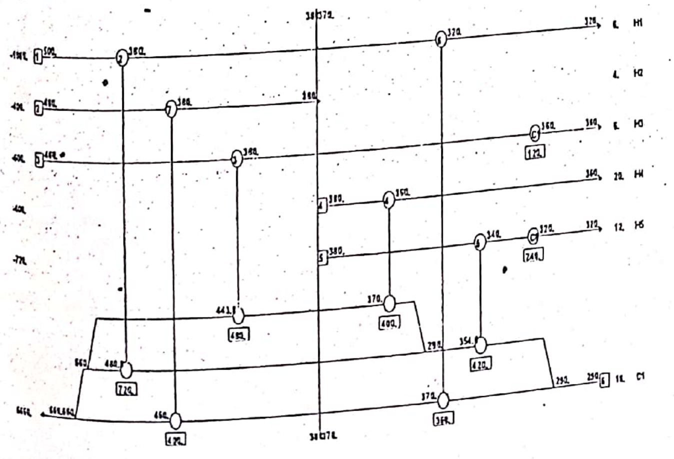

Fig.3: Grid Diagram for Example 2

Table 4: Comparison of Results for Example2 (Magnets Problem)

Method	No. of intervals	Stream splits	No. of units	TAC ($/year)	Difference (%)
Cold stream based Interval based mixed integer non-linear programming MINLP superstructure (IBMS)Isafiade and Fraser (2008)	3	1	7	595,064	5.821
Target & Supply based superstructure (T&SBS) of Azeez (2011)	6	1	7	581,954	3.490
Hot stream based Interval based mixed integer non-linear programming MINLP superstructure(IBMS) of Isafiade and Fraser (2008b)	7	1	7	581,942	3.487
Supply & target based superstructure S&TBS (Type 1) (2012)	7	1	7	581,942	3.487
Supply based superstructure (SBS) of Azeez et al. (2013)	6	1	8	580,023	3.146
Supply & target based superstructure S&TBS (Type 2) (2012)	7	1	10	577,602	2.716
Stage wise superstructure (SWS) of Yee and Grossmann (1990)	5	1	7	576,640	2.545
Genetic algorithm (GA) of Lewin (1998)	-	2	9	573,205	1.934
Pinch technique (HINT), present study	-	2	8	562,331	0.00

Example 3 Krishna and Murty (2007)

This example is an aromatic plant problem reported in previous works (Linnhoff and Ahmed, 1990; Lewin, 1998; Krishna and Murty, 2007) that attempted to determine cost optimal network of heat exchangers. The problem consist of four hot streams and five cold streams having significantly different heat transfer coefficients as shown in Table 5 with its grid diagram in Figure 4. The result obtained using HINT software shows that two (2) stream splits and eleven (12) number of units was obtained. Total annual cost of $2.881 million/year was obtained and is the best when compared to the least minimum annual cost reported literature as shown in Table 6. The least number of splits obtained in previous works for this problem is 2 which correspond to the number obtained in this work. The minimal number of splits signifies reduction in the cost of piping. Sequential match reduction approach of Pettersson (2005) gives the best minimum cost of $M2.905/year. The highest cost is that obtained by the DEM of Krishna and Murty (2007) with a cost of M$3.146/year and percentage difference of 8.30 % higher. The results obtained shows that the HINT is a robust tool capable of identifying optimal network of heat exchangers proved by the annual cost, splits and number of units obtained which can be linked to the optimal placement of heat exchangers through best matches selection and ΔTmin optimization.

Table 5: Stream and Cost Data for Example3 (Krishna and Murty, 2007)

Stream	Ts (K)	Tt (K)	F (kW K^{-1})	h (kW m^{-2} K^{-1})
H1	600.15	313.15	100	0.50
H2	493.15	433.15	160	0.40
H3	493.15	333.15	60	0.14
H4	433.15	318.15	400	0.30
C1	373.15	573.15	100	0.35
C2	308.15	437.15	70	0.70
C3	358.15	411.15	350	0.50
C4	333.15	443.15	60	0.14
C5	413.15	573.15	200	0.60
Hot oil	603.15	523.15	-	0.50
CW	288.15	303.15	-	0.50

Plant lifetime = 5 years; rate of interest = 0%; exchanger cost = $10,000+350(A) (A in m^2); cost of hot oil = 60 ($/year)/kW; cost of cooling water (CW) = 6 ($/year)/kW.

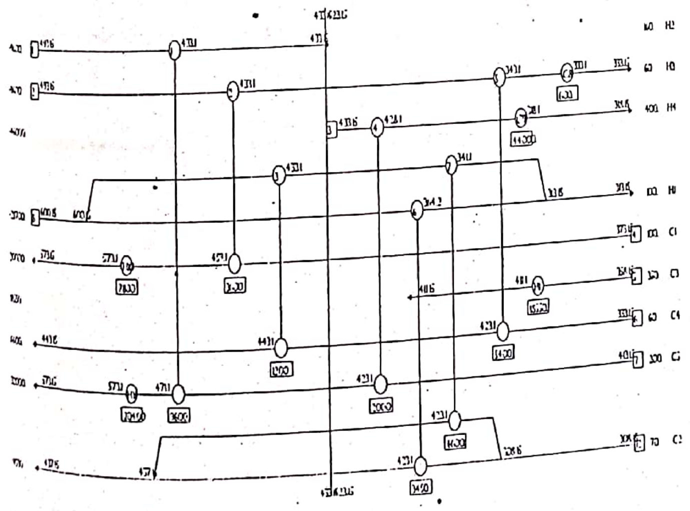

Fig. 4: Grid Diagram for Example 3

Table 6: Comparison of Results for Example 3 (Krishna and Murty, 2007)

Method	Stream splits	No. of units	Cost (M$/year)	Difference (%)
Differential evolution method (DEM) of Krishna and Murty (2007)	2	-	3.146	9.19
Block decomposition technique of Zhu et al. (1995)	0	10	2.980	3.43
Supply & target based superstructure (S&TBS) (Type 1) of Azeez et al. 2011	3	13	2.979	3.40
Supply based superstructure(SBS) of Azeez et al. (2013)	6	14	2.976	3.29
Linnhoff and Ahmad (1990)	0	13	2.960	2.74
Genetic algorithm (GA) of Lewin (1998)	0	11	2.946	2.25
Differential evolution method (DEM) of Krishna and Murty (2007)	0	15	2.942	2.11
T&SBS of Azeez et al. (2011)	7	17	2.922	1.42
Sequential match reduction approach of Pettersson (2005)	7	17	2.905	0.83
Pinch technique (HINT), present study	2	12	2.881	0.00

1. CONCLUSION

The search for optimal cost of heat exchanger network by previous researchers for three (3) different reported problems has been examined using HINT software to examine its potentials. The HINT software has been proven to be suitable for the solution of such problems and the potentials of remaining problem analysis (RPA) is revealed. The extent of HINT performance varies with the type of problem but is excellently adequate in all heat exchanger network problems solution. The result shows that using HINT, there was a successful reduction in the minimum number of units, additional piping cost and the overall total annual cost.

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