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Matrix Representation of the Grid Diagram for Heat Exchanger Networks

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Heat Exchanger Networks (HENs) are commonly represented on grid diagrams (GD). However, the traditional GD has some drawbacks with regard to calculation and evaluation. In this paper a representation of HENs in the form of a matrix called HEN Steam Matrix (HENSM) is presented. This numerical way has some advantages over graphical representation. In HENSM the heat exchangers are arranged in orderly fashion making it easier for engineers during synthesis or retrofit analysis. HENSM is able to track temperature differences directly by numerical values. This reveals the Process Pinch, Network Pinch and the other potential Pinches. The matrix can also serve as an input and output interface for software tools. A retrofit case study is demonstrating the matrix use. The amount of energy can be recovered with different heat paths from the same heater to various coolers and the capital and payback period are compared among the heat paths.

1. Introduction

Pinch Analysis and Process Integration have been pioneered by Linnhoff (1979). It offers a systematic analysis of performance for targeting and HEN design (Linnhoff et al., 1994). It helps saving significant amount of energy contained in utilities (Klemeš, 2013). To achieve the targets, the HEN should be designed according to the Pinch Design Method (Klemeš et al., 2013). The technology advance has brought Mathematical Programming (MP) into energy saving analysis as well, where a model and superstructure for HEN synthesis are developed. The MP approach is largely based on this superstructure type. For the overview see e.g. Klemeš and Kravanja (2013).

Regardless the method used in the analysis, the HENs synthesised, analysed or retrofitted are mostly represented on grid diagram (GD) (Smith, 2005). The GD is a graphical representation consisting of streams represented by horizontal arrows. The streams are linked vertically by heat exchangers. The location of the Process Pinch can be shown on the GD. Asante and Zhu (1997) formulated the Network Pinch concept and used it for HEN retrofit. However, Network Pinch is not shown directly on the GD without additional calculation.

Another graphical visualisation tool was developed by Lakshmanan and Bañares-Alcántara (1996), called Retrofit Thermodynamic Diagram (RTD). It considers the temperature span and CPs of process streams simultaneously. In the diagram the heat content of streams and heat exchanged between streams are clearly shown. Wan Alwi and Manan (2010) developed a graphical tool called Streams Temperature vs. Enthalpy Plot (STEP) for simultaneous targeting and design of HEN. The extension of this tool to become numerical called Segregated Problem Table Algorithm (SePTA) was developed by Wan Alwi et al. (2013). The result of the work is represented on authors' newly developed representation called SePTA Network Diagram (SND).

Two works have been published representing HENs in different graphical ways to cope with the problem of not showing Pinches. Gadalla (2015) plotted temperatures of hot process streams versus cold process streams. Each existing heat exchanger is represented by a straight arrow with slope proportional to the ratio of heat capacities and flows. Yong et al. (2014) modified the RTD into Shifted Retrofit Thermodynamic Diagram (SRTD). The temperatures of hot streams are shifted to be colder to allow for

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feasible temperature differences. The Pinches are shown more explicitly by the links at the ends of every heat exchanger.

However, all these graphical HEN representations have some limitations. (i) The data accuracy is reduced using graphical representation. Exact values cannot be retrieved directly. (ii) The graphical representation becomes complicated when there are too many heat exchangers in the HEN. (iii) Important data such as temperature differences at the ends of heat exchangers are not able to be directly shown on the graph.

In this paper the suggestion to represent HEN numerically in a matrix form is proposed. HEN Steam Matrix (HENSM) is able to improve the discussed limitations faced by graphical representations. However, HENSM does not provide the same inside as the graph and should be used in the combination. The data for each heat exchanger are recorded numerically and can be retrieved directly and accurate. This matrix is also able to record a HEN with high number of heat exchangers, as it does not use lines or connectors. This is a well-organised representation and is able to help to process the analysis. Temperature differences can be traced and evaluated directly, which helps in locating Pinches. During heat path tracing in retrofit analysis, the bottleneck heat exchanger limiting the heat recovery can be determined directly. Using the proposed matrix format to represent a HEN helps to increase the clarity.

This suggested HEN representation can be used as an alternative tool for synthesis and retrofit. It can also be used to generate graphical HEN visualisation such as GD and SRTD. In Pinch Analysis it is stated that there should be no heat transfer across the Pinch. The streams can be split into above and below Process Pinch in HENSM during HEN synthesis. To avoid heat transfer from hot stream above Pinch to cold stream below Pinch, HENSM can remind user from these forbidden matches. Any incorrect and thermodynamically infeasible matches can be seen using the temperature differences column. HENSM provides better notification of Network Pinch. How the heat exchangers behave along a heat path can be observed, using the temperature differences, which is important for the retrofit. The bottleneck heat exchanger limiting the heat recovery can be determined. The matrix implementation is demonstrated by retrofit analysis. It can also be used as an input and output interface for software tools, avoiding double input procedure.

2. Matrix Construction and Structure Description

Streams are divided into smaller unit called segments, where one hot segment exchanges heat with exactly one cold segment. Each segment may also additionally exchange heat with a utility. HENSM consists of hot and cold stream segments intersecting with each other, where the intersections are placeholders for duties of recovery or utility heat exchangers. Referring to HENSM sketch in Figure 1, the data of hot stream segments such as heat capacity flowrate (CP), supply and target temperatures are at the top. The segment placeholders run vertically from top to bottom as shown using vertical arrow in Figure 1. The arrangement of these hot stream segments is first according to hot stream. If more than one segment is found for a hot stream, then the segments are arranged according to descending order of supply temperature. If a hot stream segment is served by a cooler, the duty of the latter is placed at the end of the vertical arrow. The cold stream segments start from the left and run horizontally to the right, shown using a horizontal arrow. The cold stream segments are arranged first according to the cold streams. For each cold stream the segments are arranged in ascending order of supply temperature. Similarly for a cold segment with heater, its duty is shown at the end of the horizontal arrow.

The temperature difference between hot and cold stream segments are calculated at hot ends (HETD) and cold ends (CETD) of all heat exchangers. When Pinch is considered in the analysis, minimum allowable temperature difference (ΔT_{min}) is deducted from HETD and CETD, resulting in shifted parameters called HETD* and CETD*. These two parameters should have non-negative values at all time, for ensuring feasible heat exchange. A zero value at one of the ends of the heat exchanger indicates that that is a Pinch Point (Process or Network Pinch).

The hot and cold stream segments intersect each other in the recovery heat exchanger area in the middle of HENSM. The recovery heat exchanger duties are recorded in the intersection cells. To ensure that each hot stream segment exchanges heat with exactly one cold stream segment, there should be no other values in the other cells in the concerned row and column.

HENSM keeps precise values of temperatures and duties of each heat exchanger. Besides that, temperature differences at the ends of heat exchangers which cannot or are difficult to represent graphically can be traced and evaluated using the matrix. This helps locating the Process and Network Pinches. The HETD* and CETD* values also indicate how close are heat exchanger ends to Pinching condition. HENSM can also accommodate specifying different ΔT_{min} values in different parts of the network.

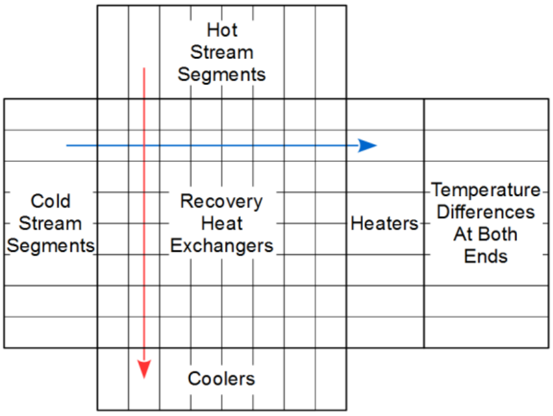

Figure 1: Sketch of HENSM as HEN representation

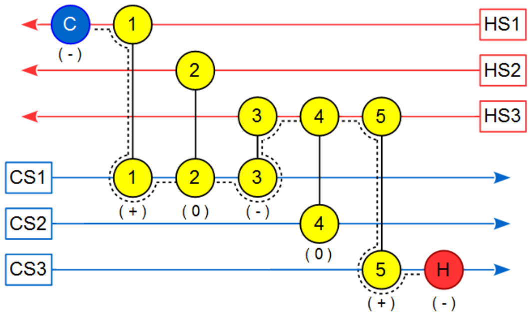

Figure 2: Heat path showing different kinds of heat exchangers

3. Heat exchangers considered along a heat path

Consider Figure 2 where an example of a heat path on a HEN grid diagram is shown (Varbanov and Klemeš, 2000). Along the heat path there are all four kinds of heat exchangers. In this context, they are grouped into positive pass-through heat exchangers (i.e. 1 and 5), negative pass-through heat exchangers (i.e. 3), hot-fixed pass-by heat exchanger (i.e. 2) and cold-fixed pass-by heat exchanger (i.e. 4).

With the heat recovery increased over this heat path, the duties of cooler and heater decrease. To cope with energy changes, the positive pass-through heat exchanger increases its duty while negative pass-through heat exchanger decreases its duty. The supply temperatures for both hot and cold stream segments in positive pass-through heat exchangers do not change during the analysis. The target temperatures for both hot and cold stream segments in negative pass-through heat exchangers do not change during the retrofit analysis. For a hot fixed pass-by heat exchanger inlet and outlet temperatures of hot stream segment do not change during the analysis. For cold fixed pass-by heat exchanger inlet and outlet temperatures of the cold stream segment do not change during the analysis.

A Network Pinch would align at a heat exchanger, at one end, after reaching the maximum heat recovered. Depends on how the heat exchanger behaves in the heat path, the maximum heat recovered for this heat exchanger is the lower value between cold end to Pinch (CETP) and hot end to Pinch (HETP) calculated using Eq(2) to Eq(9) in Table 1. The lowest value among these heat exchangers is the Maximum Allowable Heat Transferred (MAHT) for this heat path.

The calculation of additional area for all heat exchangers starts from determining the new values of HETD and CETD. Using these two values the log mean temperature difference for each heat exchanger can be calculated directly. Some simple assumption can be such as the overall heat transfer coefficients are kept constant to find the new area for heat exchanger.

The cost of building the new heat exchanger used in the case study is calculated following the equation found in Jiang et al. (2014) where A is in m².

$$C\ (\$) = 44{,}186 + 388.8 \times A \qquad (1)$$

Table 1: Equations to determine the Network Pinch for all four discovered kind of heat exchanger

Heat Exchanger Kind				
Positive Pass-through	$CETP = CETD^{*} \times CP_C$	(2)	$HETP = HETD^{*} \times CP_H$	(3)
Negative Pass-through	$CETP = CETD^{*} \times CP_H$	(4)	$HETP = HETD^{*} \times CP_C$	(5)
Hot Fixed	$CETP = CETD^{*} \times CP_C$	(6)	$HETP = HETD^{*} \times CP_C$	(7)
Cold Fixed	$CETP = CETD^{*} \times CP_H$	(8)	$HETP = HETD^{*} \times CP_H$	(9)

4. Illustrative Case Study

A case study is used to demonstrate the use of HENSM. A simplified preheat train is adapted from Jiang et al. (2014). The stream data is given in Table 2. All hot streams exchange heat with the only cold stream. There are four coolers and a heater, while heat transfers between streams are done using seven heat exchangers. The HEN Grid Diagram is given in Figure 3.

Table 2: Stream properties for illustrative case study

Stream	Name	Supply Temperature (°C)	Target Temperature (°C)	Heat Capacity Flowrate (kW/°C)	Duty(kW)
1	H1	310	95	86.0	18,490
2	H2	299	120	21.4	3,831
3	H3	273	250	184.7	4,248
4	H4	230	95	23.5	3,173
5	H5	206	178	129.4	3,623
6	C1	52	360	143.9	44,321

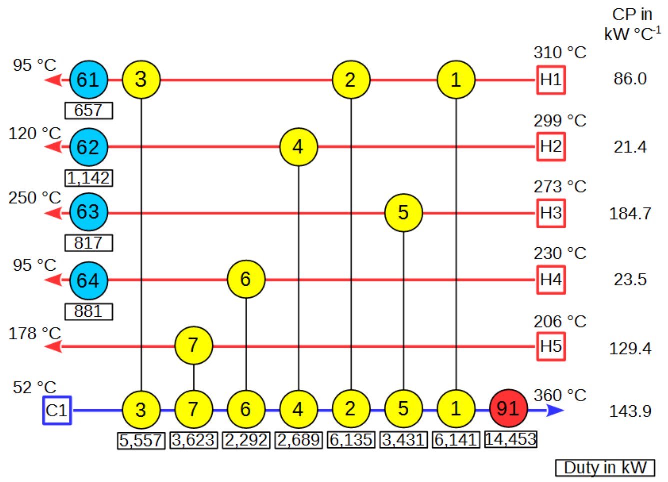

Figure 3: Current HEN represented by the Grid Diagram (after Jiang et al., 2014)

Table 3: HENSM representation of the case study

					Hot Stream	H1	H1	H1	H2	H3	H4	H5	
					CP (kW/°C)	86	86	86	21	185	24	129	
					TS (°C)	310	239	167	299	273	230	206	
					TT (°C)	239	167	103	173	254	133	178	
HEX Name	Cold Stream	CP (kW/°C)	TS (°C)	TT (°C)									Heater Duty (kW)
3	C1	144	52	91				5,557					
7	C1	144	91	116								3,623	
6	C1	144	116	132							2,292		
4	C1	144	132	150					2,689				
2	C1	144	150	193			6,135						
5	C1	144	193	217						3,431			
1	C1	144	217	260		6,141							14,453
					Cooler Duty (kW)			657	1,142	817	881		

From HENSM shown in Table 3, it can be seen that there are several heat paths for recovery. Due to space constraint, the shifted temperature differences at the heat exchanger ends are shown separately in Table 4. All heat paths that can be formed from cooler 61 to heater 91 are listed in Table 5, along with the involved heat exchangers. Using HENSM, the heat path can be start from the cooler column, tracing up until it reaches he heat exchanger duty, the user can choose either continue up direction to move between the same stream segments, or move left to cold stream segment. It is then continue to the next duty until the path ends at a heater. In Table 6, the MAHT values for all heat paths are calculated using the equations from Table 1. The associated total capital costs are shown in Table 6.

In Table 6 heat path 2 has highest value of MAHT, followed by heat path 1. However, the actual amount of heat that can be recovered is actually limited by the duty of cooler 61. Heat paths 1 and 2 recover the same final amount of heat (in competition). Table 6 also shows that heat path 3 and 4 have the same potential heat exchanger but heat path 2 has different MAHT. It is due to heat exchanger 2 having different roles in these heat paths. Heat path 2 is limited by low CETD* of heat exchanger 2 and CP of cold stream C1 as heat exchanger 2 is a positive pass-through heat exchanger. Heat path 3 and 4 are limited by low CETD* of heat exchanger 2 and CP of hot stream H1.

Table 4: HETD and CETD* for all heat exchangers*

HEX Name	HETD*	CETD*
3	66.6	40.6
7	80.2	77.4
6	88.3	6.7
4	138.6	31.6
2	35.6	6.8
5	46.1	51.4
1	40.4	11.7

Table 5: Details for all heat paths

Heat Path		Pass-through HEX		Pass-by HEX		All Involving HEX
No.	Path	Positive	Negative	Hot Fixed	Cold Fixed	
1	61 > 3 > 91	3	-	7, 6, 4, 2, 5, 1	-	3, 7, 6, 4, 2, 5, 1
2	61 > 2 > 91	2	-	5, 1	3	3, 2, 5, 1
3	61 > 1 > 91	1	-	-	3, 2	3, 2, 1
4	61 > 3 > 2 > 1 > 91	3, 1	2	7, 6, 4	-	3, 7, 6, 4, 2, 1

Table 6: MAHTs and capital costs for all the heat paths found

Heat Path No.	Potential Pinch HEX	MAHT (kW)	Final Heat Recovered (kW)	Energy Saving ($/y)	Total Capital Cost ($)	Payback Period (y)
1	6	946.1	657.0	266,413	368,364	1.38
2	2	978.5	657.0	266,413	256,674	0.96
3	2	584.8	584.8	237,136	209,929	0.89
4	2	584.8	584.8	237,136	369,690	1.56

The energy price is taken at the same source as the capital cost for heat exchanger Eq(1). Price for hot utility is taken at 400 $ kW^{-1} y^{-1} and cold utility at 5.5 $ kW^{-1} y^{-1}. (Jiang et al., 2014)

Heat path 1 has higher capital cost but same final heat recovered as heat path 2. This is due to heat path 1 involving more heat exchangers than heat path 2. Although heat path 3 has the fastest payback period, it recovers smaller amount of heat compared to heat path 2. Heat path 2 maybe chosen if the investor decides to focus on saving more energy. This example has illustrated how to perform HEN path analysis on the developed matrix. The analysis considered all possible paths from cooler 61 to heater 91. As it is shown in Table 6, from the same cooler to heater, there are at least four heat paths can be obtained. Each heat paths has different potential Pinched heat exchanger and MAHT. Using HENSM, comparisons between energy saved and cost involved can be made among the heat paths.

5. Conclusions

A matrix representation of HENs is proposed in this paper to support synthesis or retrofit tasks. It can be well-organised and can help engineers in analysing the system with preserved accuracy. HENSM records all the temperatures, temperature differences and duties of all heat exchangers in a HEN. Using the temperature differences at heat exchanger ends, the matrix is able to support the location of Process and Network Pinches. During retrofit Path Analysis, the potential of a heat exchanger in becoming a Network Pinch is shown in the matrix. HENSM is demonstrated on a case study. During the retrofit analysis more than one heat path starting from the same cooler to the same heater was found. Further energy and economy analysis shows that different heat paths have different Potential Network Pinch heat exchanger. It is due that heat exchangers act differently on different heat paths. The result from the analysis provides a retrofit solution that has the fastest payback period. The second solution also recovers higher amount of energy at a slightly longer payback period. The matrix so far cannot deal stream splitting. However, this can be overcome and has been already part of a future work.

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