An Enhanced Tool for Heat Exchanger Network Retrofit Towards Cleaner Processes

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The individual stream temperature versus enthalpy plot (STEP) is a graphical tool that can be used to simultaneously diagnose and retrofit existing heat exchanger networks (HEN). The Modified Energy Transfer Diagram (ETD) utilises the Grand Composite Curve (GCC) to provide insights on the scope for HEN retrofit and to pinpoint retrofit alternatives based on the Bridge Analysis method. Both the STEP and the Modified ETD methods are based on graphical representation of individual process streams that enable users to visually identify the potential scope for improvement in an existing HEN. It is found that, using the distance of the horizontal gap between the stream pairs of the STEP diagram can simplify the construction of the Modified ETD. The Modified ETD can help monitor the progress of HEN retrofit. This paper shows through a case study that, combining the use of STEP-ETD methods can simplify, facilitate and enhance the simultaneous targeting, diagnosis and retrofit of a HEN toward achieving cleaner processes, while yielding the same final retrofitted structure like those produced by using only the Modified ETD.

1. Introduction

Energy in the form of heat is one of the most extensively-used resources in the process industry. Heat wasted from manufacturing processes into the environment can increase the requirement of utilities, operating expenses, and also emission of carbon dioxide into the environment. Heat exchanger network (HEN) retrofit can play a part in maintaining a plant's resource and contribute toward cleaner process operations by improving its energy efficiency. Efficient heat recovery system is a clean technology option for reducing fuel requirement, saving utilities and reducing emissions. HEN retrofit methods based on Pinch Analysis have been used over the years to guide users to enhance heat recovery from processes with the aid of graphical tools.

One of the earliest Pinch Analysis-based was introduced by Tjoe and Linnhoff (1986) who proposed a HEN retrofit method that involves the setting of a conservative retrofit investment targets. Over the years, researchers have developed numerous alternative graphical visualisation tools that are aimed at making HEN retrofit easier and more convenient. Lakshmanan and Bañares-Alcántara (1996) represented the heat loads and driving forces using the Retrofit Thermodynamic Diagram (RTD). Nordman and Berntsson (2001) introduced analysis methodologies which involves eight different curves to screen retrofit options. Nordman and Berntsson (2009) also introduced the Advanced Composite Curves which can be used for HEN retrofit by solving the problem of Pinch rule violations and by identifying retrofit alternatives. Lai et al. (2017) implemented Stream Temperature vs Enthalpy Plot (STEP) diagram for HEN retrofit. The method allows users to perform HEN retrofit directly from the temperature-enthalpy graph geometry by observing the Pinch rules and a set of retrofit heuristics. The STEP retrofit method also eliminates the need for repetitive temperature and enthalpy calculations during the course of retrofit. STEP was first introduced by Wan Alwi and Manan (2010) for designing grassroots HEN. STEP shows the mapping of segments of continuous individual hot and cold process streams on a temperature versus enthalpy plot, the maximum heat allocation, the Pinch points and energy targets.

The Energy Transfer Diagram (ETD) was proposed by Bonhivers et al. (2014) who proposed the Bridge Analysis concept. ETD is a graphical tool used to identify heat transfer bridges in a HEN. The concept of Bridge Analysis

was used to produce several graphical tools for HEN design and retrofit. A heat exchanger load diagram was introduced to simplify the effort of searching for retrofit solutions (Bonhivers et al., 2015). Bonhivers et al. (2016) combined the Pinch Analysis and Bridge Analysis to solve HEN retrofit problems by correlating the Composite Curves (CC), the ETD, and the heat exchanger load diagram (HELD). Walmsley et al. (2017) introduced a Modified ETD which can be used to determine retrofit alternatives and the amount of heat transferred based on Bridge Analysis. The Modified ETD shows the location of the heat surpluses and deficits that are present in the HEN.

Recent developments on HEN retrofit have seen the emergence of the graphical tools representing individual streams being increasingly utilised as compared to the conventional CC and Grand Composite Curve (GCC). Use of individual curves allows designers to pinpoint the specific network location and the individual heat exchanger and streams that need to be retrofitted in a HEN. Both the STEP diagram and the Modified ETD retrofit methods utilise the individual stream concept, each with unique advantages of their own. This paper shows that combining the STEP and Modified ETD graphical tools can enhance the simultaneous targeting, diagnosis and retrofit of a HEN. Application of this new method on a HEN retrofit case study shows that the combined graphical tool can help simplify and facilitate the retrofit process while yielding the same final retrofitted structure like those produced by using any retrofit method, including the Modified ETD method.

2. STEP Diagram and the Modified Energy Transfer Diagram

STEP diagram can be used to represent, diagnose and retrofit an existing HEN based on the individual stream approach. Figure 1a from Lai et al. (2017) is a conceptual example of how this is done. Individual streams are plotted in pairs using shifted temperature to indicate the transfer of heat from hot streams to cold streams across a heat exchanger. The inlet and outlet temperatures of the streams can be read from the y-axis. The horizontal gap on the x-axis shows the heat load of the exchanger. The slope of the curve can be obtained from the reciprocal of the heat capacity flowrate (FCp) of the stream. STEP diagram can be used to simultaneously diagnose and retrofit existing HEN. Users can perform stream splitting and heat load division by utilising the simple graph geometry.

The Modified ETD is a plot of GCC for HEN retrofit, as shown in Figure 1b (Walmsley et al., 2017). Individual stream pairs are first translated into individual exchanger GCCs using the temperature intervals of the individual stream pairs. The Modified ETD is then constructed by stacking the GCC for each exchanger. Based on Figure 1b, GCC of the individual stream pairs at heat exchanger E1 (hot STEP 1 and cold STEP 2 in Figure 1a) is plotted first, follow by stacking the GCC of heat exchanger E2 to the right of the GCC of heat exchanger E1. The diagram contains useful information such as the Pinch point, the maximum heat recovery potential, and extent of heat recovery for the existing HEN relative to the targeted value. The Pinch temperature for the example in Figure 1 is at 160 °C and 145 °C. In this example the heat is fully recovered. Identification of maximum heat recovery from the Modified ETD is illustrated in the next section using another case study. The extreme right end of the curve in the Modified ETD shows the grassroots GCC for the existing HEN.

(a) STEP diagram   (b) Modified ETD
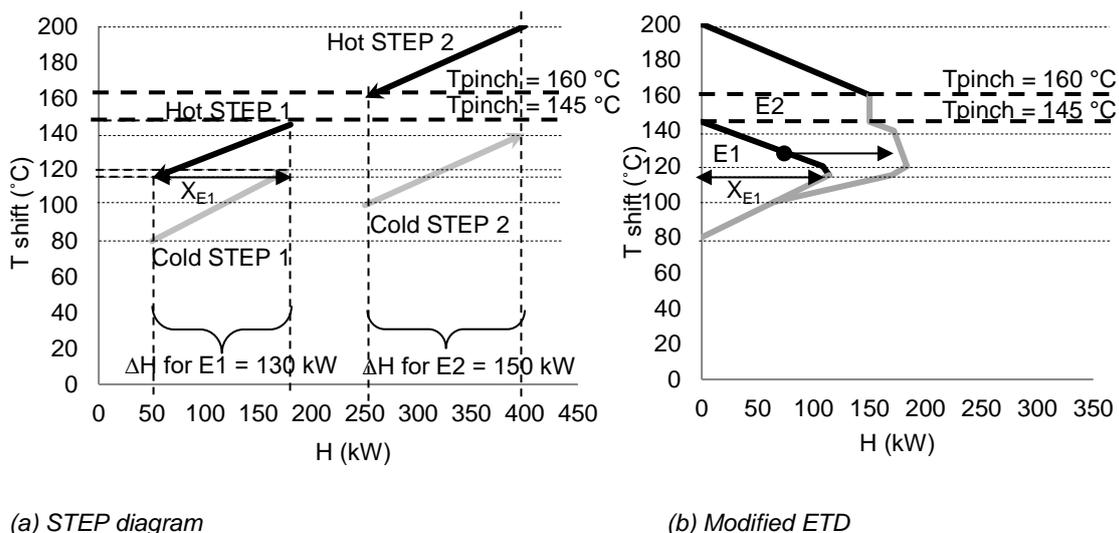
Figure 1: STEP diagram for retrofit and the Modified ETD

Some key similarities can be observed between the two graphical tools. Both tools can be used to determine cross-Pinch heat exchangers. This example shows that the cross-Pinch heat exchanger identified is heat exchanger E2 which transfers heat from hot STEP 2 to cold STEP 2. In STEP diagram, cross-Pinch heat exchangers happen when a hot STEP appears partially or fully above the Pinch and a cold STEP appears partially or fully below the Pinch point (see for example Hot STEP 2 and Cold STEP 2 in Figure 1a). In the Modified ETD, cross-Pinch heat exchanger can be identified when a heat exchanger area spreads across the Pinch (see for example heat exchanger E2 in Figure 1b). Both tools can identify exchangers with problems through direct observation. Both diagrams can determine potential matches at the same temperature range. For example, hot STEP 1 has the potential to be matched with cold STEP 1 or cold STEP 2 which are both below the Pinch point (as shown in Figure 1a). The hot stream of E1 can be matched with the cold stream at E2 (shown by the horizontal arrow in Figure 1b).

In this study, it is discovered that the Modified ETD can be constructed by direct association between the STEP diagram and the GCC of the Modified ETD. The horizontal gap between the individual stream pairs in STEP diagram is equivalent to the horizontal distance of the GCC curve (relative to the y-axis) for the respective heat exchanger in the Modified ETD. For example, the distance of X_{E1} in Figure 1a is the same as the distance of X_{E1} in Figure 1b. By taking the horizontal gap of the individual stream pairs at each temperature intervals in STEP diagram, the Modified ETD can be constructed easily. A more detailed example for the translation of STEP diagram into the Modified ETD is explained in the next section.

3. Translation of STEP diagram into Modified Energy Transfer Diagram

This section demonstrates how the STEP diagram can be translated into the Modified ETD using an illustrative case study. A retrofit problem that consists of four streams from Klemeš et al. (2014) is used as an illustrative example. The minimum temperature approach (ΔT_{min}) for this problem is 10 °C. The Pinch temperature for this case is at shifted temperature of 145 °C. The minimum heating requirement ($Q_{h,min}$) is 750 kW while the minimum cooling requirement ($Q_{c,min}$) is 1,000 kW. Figure 2 shows the grid diagram of the existing HEN.
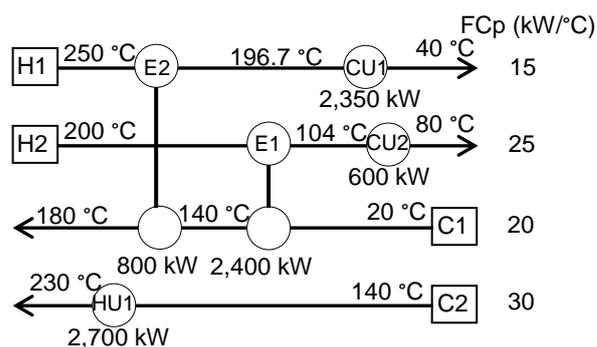
Figure 2: Grid diagram of the existing HEN

The steps involved for the translation of STEP diagram into the Modified ETD are as follow:
1. Represent the HEN in the STEP diagram according to the steps described in the work by Lai et al. (2017).

2. Plot the Modified ETD starting from heaters, coolers, and finally the process-to-process heat exchangers. The sequence of the curves can be changed according to user's preference. Note that the curves for heaters have positive slopes while for coolers, negative slopes.

Begin by drawing the heater HU1. The STEP diagram in Figure 3a shows that the heat load of heater HU1 is X_{HU1}. The distance of X_{HU1} can be directly translated into positive slope in the Modified ETD in Figure 3b using the same temperature range. Similarly, plot coolers CU2 and CU1 with the distance of X_{CU2} and X_{CU1} (read from STEP diagram in Figure 3a) but this time with negative slopes. As the curve for cooler CU1 is stacked on the right side of cooler CU2, the heat load need to be accumulated. X_{CU1} is added on X_{CU2} instead of starting from zero at the y-axis. Note that the heat load accumulation is applied to every temperature interval present in the existing HEN. Plot heat exchanger E1 using X_{E1} and Y_{E1}, and for heat exchanger E2 using X_{E2} and Y_{E2}. The right end of the Modified ETD in Figure 3b shows the grassroots GCC of the existing network. X is the maximum amount of recoverable heat.

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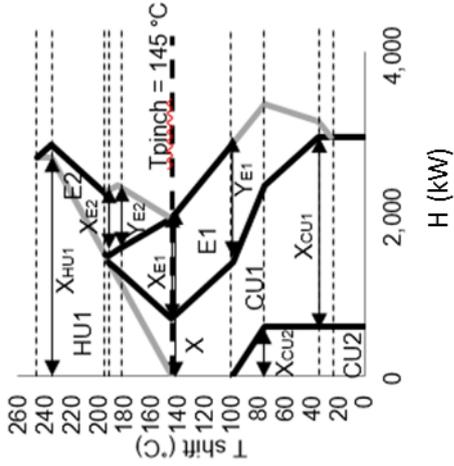
(a) STEP diagram

(b) Modified ETD

Figure 3: Translation of STEP diagram of the HEN before retrofit into the Modified ETD
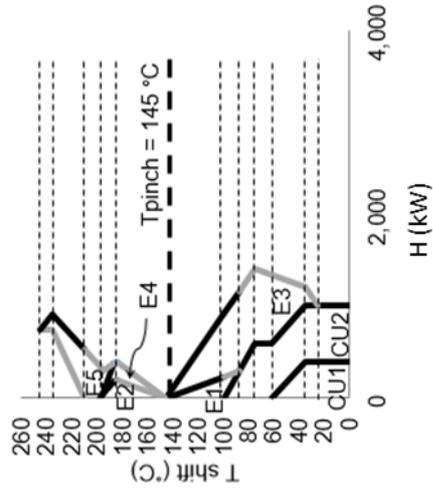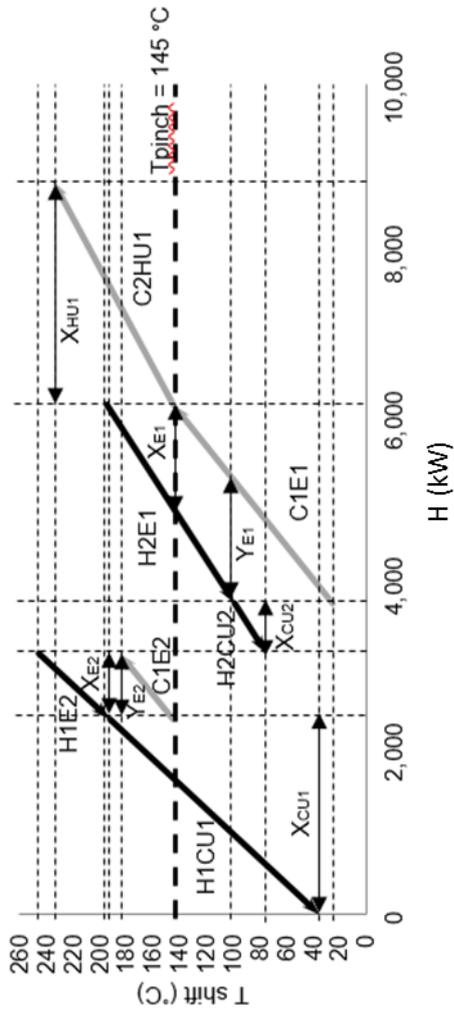
(a) STEP diagram

(b) Modified ETD

Figure 4: Translation of STEP diagram of the HEN after retrofit into the Modified ETD
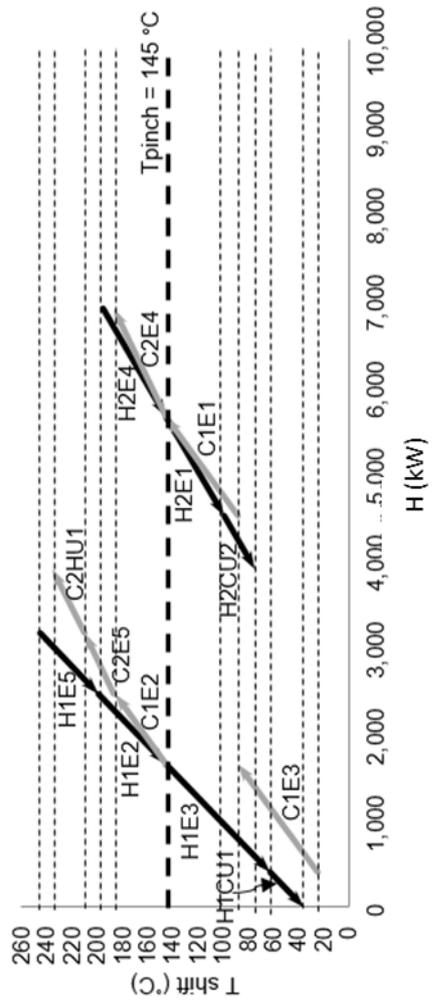
The HEN retrofit problem is solved by using STEP diagram based on the graph in Figure 3a. Above the Pinch, there are 2 hot STEPs and 2 cold STEPs. Note that C1E2 has a steeper gradient (and hence, a smaller FCp) as compared to H2E1. Matching these two STEPs may result in ΔTmin violation. To avoid this, C1E2 is moved horizontally to the left to match with stream H1. The heat load of C2HU1 is then divided into two portions to match with stream H2 and stream H1 to observe the heuristic of matching hot and cold streams of comparable temperatures. For below the Pinch, there are 2 hot STEPs and 1 cold STEPs. C1E1 is moved horizontally to be paired with stream H2 instead of stream H1 as the FCp of stream H2 is bigger than that of stream C1 while FCp of stream H1 is smaller than that of stream C1. Matching streams C1 and H1 can cause ΔTmin violation. In order to minimise network changes, and hence, the retrofit cost, the high temperature part of C1 is matched with the high temperature part of H2 without affecting the existing cooler CU2, and the remaining part of stream C1 is paired with stream H1. After retrofit, there are total of 8 units with an additional of 3 more heat exchangers to recover 1,950 kW.

The STEP diagram for the HEN after retrofit is shown in Figure 4a. It is then translated into the Modified ETD shown in Figure 4b). Note that the extreme right end of the Modified ETD shows the shape of the grassroots GCC even before retrofit is performed, and will be maintained throughout the retrofit. This grassroots GCC curve will shift horizontally to the left when users make modification to the HEN to improve heat recovery. When the curve eventually touches the y-axis at the Pinch temperature, the maximum heat recovery is achieved. The grid diagram of the HEN after retrofit is as shown in Figure 5.
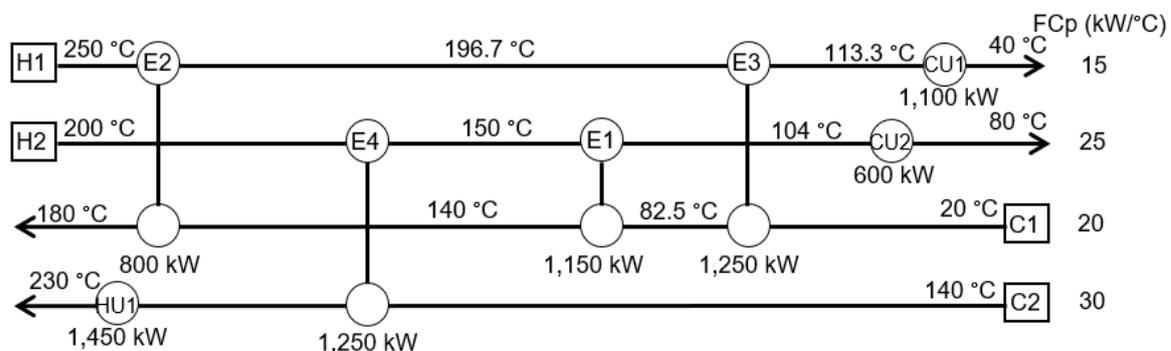
Figure 5: Grid diagram of the HEN after retrofit

4. Discussion

Table 1 compares the results obtained from using STEP diagram (this work) with the results obtained using the Modified ETD which is based on the Bridge Analysis.

Table 1: Comparison of results

	Existing network	Modified ETD (Walmsley et al., 2017)	This work
Number of units	5	8	8
Cold utility (kW)	2,950	1,000	1,000
Hot utility (kW)	2,700	750	750
Percentage reduced for cooling utility (%)		66.10	66.10
Percentage reduced for heating utility (%)		72.22	72.22

The comparison shows that both the methods achieve the same results and yield the same number of units. Combination of the STEP diagram and the Modified ETD can simplify the HEN retrofit procedure to arrive the same retrofitted structure as the one produced by the Modified ETD. The construction of the Modified ETD is facilitated by using the distance of the horizontal gap between the stream pairs in the STEP diagram. The Modified ETD can help monitor the progress of the HEN retrofit. The combination of the two graphical tools is able to simultaneously target, diagnose and retrofit existing HEN.

The combined graphical tool is found to be beneficial in solving HEN retrofit problem which involves several steps to achieve improved heat recovery. When STEP diagram is used individually, targeting is performed using other Pinch Analysis tool such as CC or Problem Table Algorithm (PTA). As for the Modified ETD, users need

to reconstruct the diagram after making every change to the existing HEN. The combined graphical tool can solve the problems faced when the graphical tools are used individually. Users can directly obtain the current heat recovery performance from the Modified ETD after alternating the HEN structure using STEP diagram. The Modified ETD can be translated directly from STEP diagram easily as compared to when it is used individually. It is recommended that the combined graphical tool can be programmed using software in the future work so that the monitoring of the simultaneous targeting, diagnosis, and retrofit existing HEN can be performed efficiently.

5. Conclusions

The STEP diagram and the Modified ETD are useful graphical tools with pros and cons of their own. This work shows that STEP diagram can facilitate and simplify the construction of the Modified ETD while the Modified ETD can represent the retrofit progress carried out by using the STEP diagram. The combination of STEP and the Modified ETD provides users with an enhanced clean technology tool for energy reduction that can assist users to simultaneously target, diagnose, and retrofit an existing HEN while yielding the same final retrofitted structure like the one produced by the Modified ETD.

Acknowledgments

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