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A New Graphical Approach for Heat Exchanger Network Retrofit Considering Capital and Utility Costs

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Development of methodologies and tools for heat exchanger network (HEN) retrofit has focused on generating retrofit solutions to address issues of vital importance to industry including energy, economy and sustainability. This work extends the use of the individual stream temperature versus enthalpy plot (STEP) to enable users to select economically feasible retrofit alternative based on capital and utility costs estimation. A new graph known as the heat exchanger area versus enthalpy plot (A vs H plot) is proposed in this work to be used in combination with the STEP diagram to enable visualisation of the area of every heat exchanger in the HEN. Note that, both graphs share the same enthalpy axis. As a result, heat exchange between the stream pairs shown in the STEP diagram can be projected to the A vs H plot. The A vs H plot contains several useful information of the existing HEN which includes the total area and the number of heat exchanger in the HEN. Firstly, retrofit options are generated by using STEP diagram based on the procedure described in a prior work. Users can later use the A vs H plot to select retrofit option which requires the minimum total heat exchanger area or to minimise the total heat exchanger area needed for the retrofit design generated based on the retrofit methodology which is introduced in this work. Capital cost needed for the retrofit options can be estimated based on total area of new heat exchangers added. Application of the combination of A vs H plot with STEP diagram on a literature case study shows that the combined graphical tools are able to provide clear visual insights to assist users identify capital-energy trade off in generating cost-effective retrofit solutions. The retrofit design and area of the individual heat exchangers in the retrofitted HEN are clearly shown in the combined graphical tools to enable users to screen the most economically viable retrofit option prior to performing economic analysis. Application of the new method on a case study shows that the annualised total cost required by the retrofit design after area minimisation is lower than that of the retrofit design before area minimisation by 3.34 %.

1. Introduction

Numerous graphical tools have been developed since Pinch Analysis was first applied for HEN retrofit (Tjoe and Linnhoff, 1986). The development of the graphical tools aims to make retrofit process interactive and to provide insights and allow better control by users in solving HEN retrofit problems. A few examples of HEN retrofit graphical tools include the Advanced Composite Curves which solves retrofit problems by identifying stream matches that violate the Pinch rules (Nordman and Berntsson, 2009), Shifted Retrofit Thermodynamic Grid Diagram (SRTGD) that supports screening of feasible retrofit options (Yong et al., 2015), and the plot of temperatures of process hot streams versus temperatures of process cold streams that can identify Cross-Pinch matches, Network Pinch and improper placement of fuel consumption (Gadalla, 2015). Recent development also includes the use of the concept of Grand Composite Curve in HEN retrofit using the Modified Energy Transfer Diagram (ETD) (Walmsley et al., 2017), and the application of individual stream temperature versus enthalpy plot (STEP) in HEN retrofit (Lai et al., 2017).
STEP diagram which is initially developed for simultaneous target and design of HEN (Wan Alwi and Manan, 2010) was applied by Lai et al. (2017) for HEN retrofit based on Pinch rules and four retrofit heuristics. STEP diagram enables a user to simultaneously diagnose and retrofit existing HEN using simple graph geometry. The method eliminates repetitive temperature and enthalpy calculations required in the conventional HEN retrofit methods. An established technique for minimum total area targeting using the conventional Composite Curves

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(CC) is introduced by Linnhoff and Ahmad (1990) as a tool for heat exchanger area visualisation. The CC is however was meant to represent the area for grassroots HEN design with limitation that the area depicted is at best, an average over the composite streams. The CC therefore does not represent the area between two individual streams exchanging heat. A new graphical tool known as the heat exchanger area versus enthalpy plot (A vs H plot) is introduced in this work which allow visualisation of heat exchanger area for retrofit purpose, between individual hot and cold streams exchanging heat. The new graphical tool is combined with the STEP diagram to provide further insights on the heat exchanger area for the purpose of capital and utility costs minimisation in HEN retrofit.

2. New Graphical Approach

The new graphical approach comprises the combination of two graphical tools and a methodology to further improve the retrofit design for capital and utility costs minimisation.

2.1 Graphical Tools

STEP diagram represents individual process streams in pairs on a temperature-enthalpy diagram (see Figure 1a for example). Individual stream profiles which include the inlet and outlet shifted temperature of the process streams, heat load at the heat exchangers, heat capacity flowrate (FC_p), and Pinch Point are shown in the diagram. In a STEP diagram, hot stream is represented by arrow pointing downward while cold stream is represented by arrow pointing upward. Gradient of the curve shows the reciprocal of FC_p of the individual process stream. Shifted temperature of process streams can be read from the vertical scale. For hot stream curve, the higher end shows the shifted inlet temperature while the lower end shows the shifted outlet temperature. For cold stream curve, the shifted inlet temperature is shown at the lower end while the shifted outlet temperature is shown at the higher end. Individual hot and cold streams which are paired up in a heat exchanger shares the same heat load range. Heat load at the heat exchanger can be read from the horizontal axis. Figure 1a illustrates the STEP diagram for a simple example showing heat exchange between two process streams. ‘H1CU1’ indicates stream segment of hot stream ‘H1’ that requires cold utility ‘CU1’. ‘H1EX1’ indicates stream segment of hot stream ‘H1’ which is matched with stream segment of cold stream ‘C1’ at heat exchanger ‘EX1’. Similarly, ‘C1HU1’ indicates cold stream segment at cold stream ‘C1’ that requires hot utility ‘HU1’. Stream segment ‘H1CU1’ has an inlet shifted temperature of 118 °C and an outlet shifted temperature of 55 °C. Heat load at ‘CU1’ is 1,900 kW.

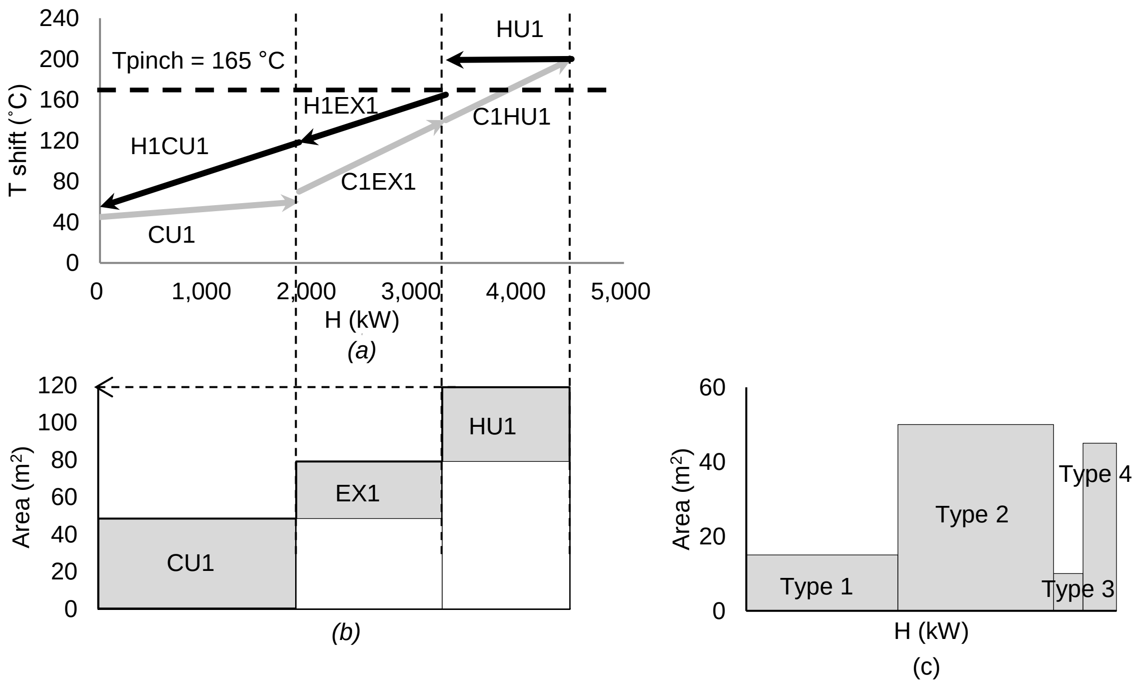

Figure 1: New Graphical Approach (a) STEP diagram, (b) A vs H plot, (c) Types of heat exchanger blocks in A vs H plot.

A new graphical tool known as the A vs H plot is introduced for the visualisation of the heat exchanger area distribution across the HEN (see Figure 1b for example). Every individual heat exchanger is represented as a block on the diagram. The width of the block indicates the heat load being exchanged while the height of the block indicates the heat exchanger area (calculated using Eq(1) in section 2.2). Both STEP diagram and the A vs H plot shares the same enthalpy axis. Due to this, the two graphical tools can be drawn on the same enthalpy scale so that area of heat exchanger for every stream pair in the STEP diagram can be mapped accordingly on the A vs H plot. Figure 1 shows how the two graphical tools are related to each other to provide further insights of the area of every heat exchanger in the HEN. When the individual blocks are stacked up vertically, the highest end of the last block shows the total heat exchanger area in the HEN. In this case, the total heat exchanger area of the HEN is 120 m^2, shown by the horizontal dashed arrow in Figure 1b. The difference between the total heat exchanger area of HEN before and after retrofit is vital for the estimation of capital cost required for retrofit design in order to guide users during selection of best retrofit option that incur the minimum possible additional heat exchanger area.

The blocks representing the heat exchanger area and heat load at the heat exchangers can be categorized into four different types. Figure 1c illustrates the four types of blocks in the A vs H plot. Type 1 block has large width with small height, indicating heat exchanger with large heat load and small heat exchanger area. It is usually a result of stream pair with big heat load and big temperature difference. It is the most preferred situation as only small area is needed to cater large amount of heat load. Type 2 block has large width and large height, indicating heat exchanger with large heat load and large heat exchanger area. Type 3 block has both small width and height, indicating small heat exchanger area for small heat load. Type 2 and Type 3 blocks are acceptable as suitable heat exchanger areas are employed to cater the amount of heat exchange of the process streams. However, Type 2 block is preferable as the savings that can be achieved by Type 3 block is not significant since it only caters small heat load. Type 4 blocks has small width and large height, indicating large heat exchanger area is used for small amount of heat exchange. Retrofit design with Type 4 block is to be avoided as far as possible as it is not economically feasible to be applied. The order of preference of heat exchanger blocks in the A vs H plot decreases from Type 1, Type 2, Type 3, and lastly Type 4.

2.2 Methodology

HEN retrofit using the new graphical approach can be performed based on the following steps.

1. Diagnose and retrofit existing HEN following the steps stated in a prior work (Lai et al., 2017).
2. Calculate the area for every heat exchanger in the retrofit design generated in step 1 using Eq(1).

$$A = \frac{Q}{U \times \Delta T_{LM}} \tag{1}$$

where Q is the heat load at the heat exchanger, U is the heat transfer coefficient, A is the area of heat exchanger, and ΔT_{LM} is the logarithmic mean temperature difference which can be calculated using Eq(2).

$$\Delta T_{LM} = \left((T_{h1} - T_{c2})(T_{h2} - T_{c1}) \left(\frac{(T_{h1} - T_{c2}) + (T_{h2} - T_{c1})}{2} \right) \right)^{\frac{1}{3}} \tag{2}$$

3. Construct the A vs H plot using the area calculated and the enthalpy values from STEP diagram. Note that the diagram shares the same enthalpy scale with STEP diagram (see Figure 1 for example).
4. Analyse the heat exchanger area of the retrofit design using the A vs H plot. Identify Type 2 and Type 4 blocks from the diagram for further modification to minimise the area required.
5. Perform modifications by changing heat recovery matches, shifting heat load, or by eliminating heat exchangers. Effects of each type of modification is explained in the following subsection.
6. Repeat steps 4 and 5 until retrofit design with minimal area requirement is obtained, the design can now be finalised.

Effect of Each Type of Modification

The effects of each type of modification made to the retrofit design are being explained.

- Change matches between heat exchangers
  This option can be applied for heat exchanger of Type 4 block in which large heat exchanger area is required to recover small heat load. In order to minimise the heat exchanger area, and hence, the capital cost, heat exchanger of Type 4 block can exchange heat with other heat exchanger with small heat exchanger area, such as heat exchanger of Type 3 block, provided that the minimum temperature approach (ΔT_{min}) is not violated. Doing so allows the large heat exchanger area to be evenly distributed to heat exchangers with smaller areas, and ultimately reduce the total heat exchanger area required to recover the same amount of heat load. Besides minimising area, this option can also be applied to reduce utility cost. For example, the

stream that requires expensive, higher-quality utility can be re-matched with process stream, whereas the remaining individual stream from the original pair can be matched with a cheaper utility.

- Shift the heat load from one heat exchanger to another
  This option can be applied for heat exchanger with Type 2 or Type 4 block when there is another heat exchanger located on the same process stream. Usually heat exchanger of Type 2 block is located near the Pinch. The large heat exchanger area can be reduced by shifting its heat load to the adjacent heat exchanger located along the same process stream that may have a larger temperature driving force and smaller heat exchanger area. Besides, the small heat load at heat exchanger of Type 4 block can also be shifted to the adjacent heat exchanger along the same process stream to reduce the heat exchanger area required, as well as the number of unit in the HEN.
- Eliminate heat exchanger
  This option can be applied for heat exchanger with small heat load, especially for heat exchanger of Type 4 block which require large heat exchanger area to recover small heat load. Heat exchanger of Type 4 block can be selectively eliminated if the heat load cannot be shifted to another heat exchanger. Heat exchanger of Type 4 block is usually not economically feasible to be implemented.

Modification can be performed according to user's decision. The ultimate target is to achieve the minimum annualised capital and utility costs of the retrofit design.

3. Case Study

The proposed new graphical approach is applied on a four streams literature case study from Klemeš et al. (2014). The case study has a ΔT_{min} of 10 °C and the Pinch temperature is at 145 °C. Minimum heating requirement ($Q_{h,min}$) is 750 kW while the minimum cooling requirement ($Q_{c,min}$) is 1,000 kW. The existing HEN firstly undergo retrofit process according to the retrofit approach by Lai et al. (2017). Grid Diagram of the retrofit design obtained is as shown in Figure 2. The result of the retrofit in STEP diagram is as shown in Figure 3a. Area of the heat exchanger is calculated using Eq(1) and Eq(2) and by assuming U to be constant for all heat exchangers at 500 W/m^2.K. The area calculated and the enthalpy value from STEP diagram are used to construct the A vs H plot, as shown in Figure 3b. It is observed from Figure 3b that the retrofit design has a total of seven units with five process-to-process heat exchangers, one heater, and one cooler. In the A vs H plot, existing unit is represented by darker grey while additional unit is represented by lighter grey. All five process-to-process heat exchangers are new heat exchangers as the additional heat exchanger area required exceeds 100 % of the existing heat exchanger area. Heat exchanger 'EX1' has the largest area of 200 m^2, follow by the second largest heat exchanger 'EX4' with area of 180 m^2. Heat exchanger 'EX3' has the smallest area among all the heat exchangers. The total heat exchanger area for the retrofit design is 653 m^2. All the heat exchangers in the A vs H plot for this case are Type 2 and Type 3 blocks, hence are considered acceptable.

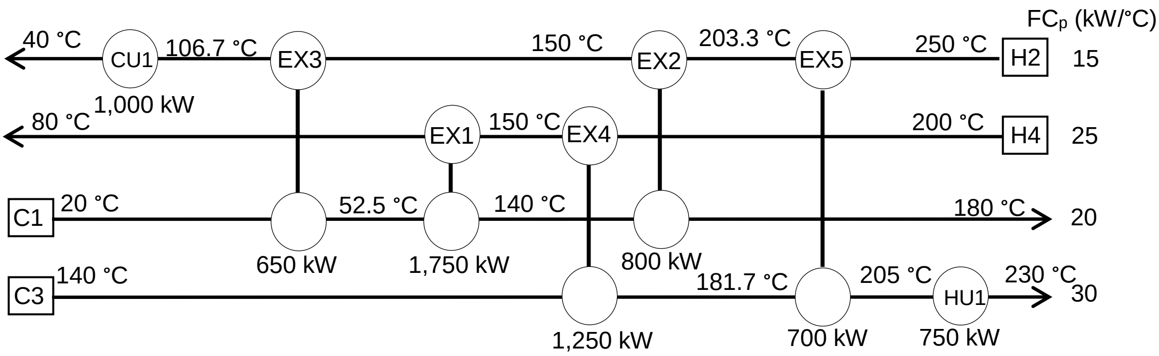

Figure 2: Grid Diagram of the HEN before area minimisation

Heat exchanger 'EX1' with the largest area is selected for minimisation by assuming that it is a new heat exchanger which is to be added to the network. Based on Figure 3a, heat exchanger 'EX1' consists of stream segments from hot stream 'H4' and cold stream 'C1'. The two stream segments are matched together according to the Pinch rule that stated FC_p of stream leaving the Pinch shall be greater than FC_p of stream entering the Pinch (Linnhoff and Hindmarsh, 1983). Cold end of stream 'C1' is then paired with hot stream 'H2'. In order to minimise the area at heat exchanger 'EX1', part of stream segment of cold stream 'C1' at heat exchanger 'EX1' can be shifted to heat exchanger 'EX3' since stream segment of hot stream 'H2' at heat exchanger 'EX3' has higher temperature than stream segment of hot stream 'H4' at heat exchanger 'EX1' which allow feasible heat transfer to cold end of cold stream 'C1'. By shifting part of the stream segment of cold stream 'C1' from heat exchanger 'EX1' to heat exchanger 'EX3', the heat exchanger area of 'EX1' is reduced from 200 m^2 to 150 m^2 while heat exchanger area of 'EX3' is increased a little from 14 m^2 to 44 m^2 (see Figure 3b and 5b for example). The cold utility requirement at cooler 'CU1' can be decreased from 1,000 kW to 400 kW. Existing cooler 'CU2' can be maintained at cold end of hot stream 'H4' to recover the remaining heat load of 600 kW which is deducted from cooler 'CU1'. The 1,000 kW of more expensive cold water can now be reduced to 400 kW and the remaining 600 kW can be cooled using cheaper cooling air. STEP diagram and A vs H plot of the retrofit design after area minimisation is as shown in Figure 3c and d, while the Grid Diagram is shown in Figure 4.

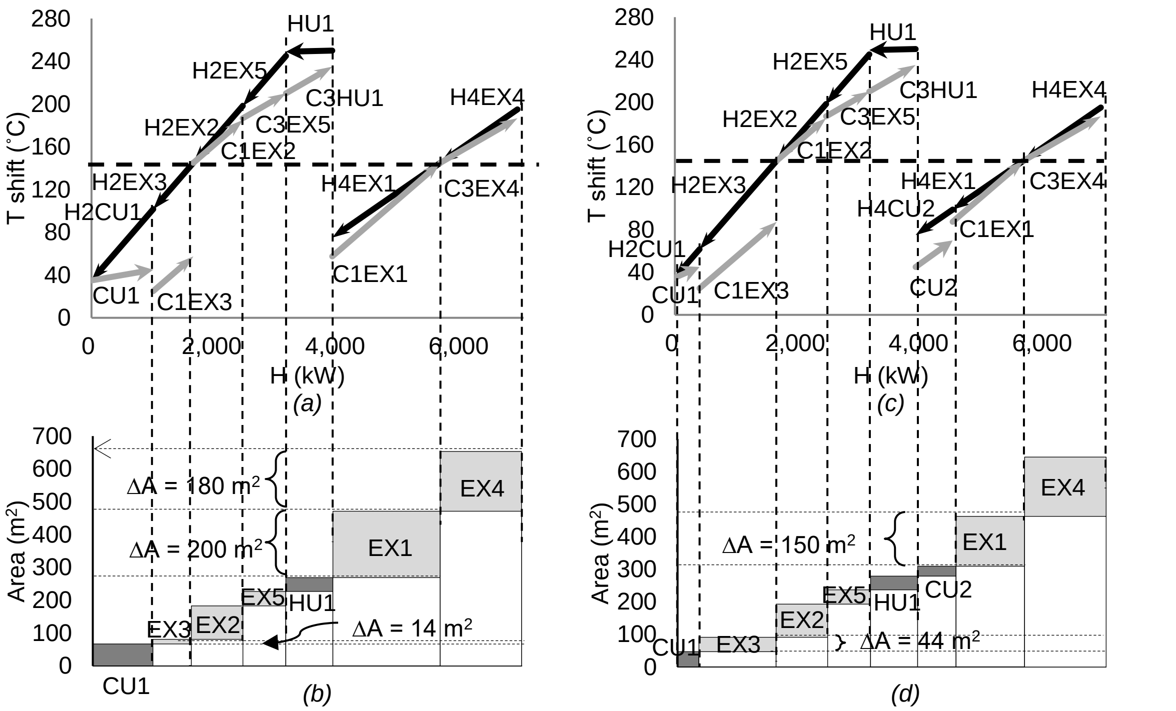

Figure 3: Retrofitted HEN before area minimisation (a and b). Retrofitted HEN after area minimisation (c and d)

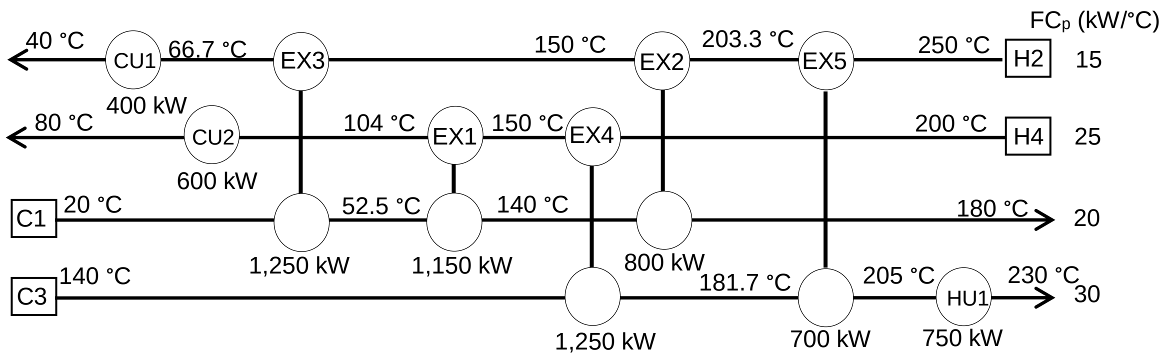

Figure 4: Grid Diagram of the HEN after area minimisation

3.1 Results and Discussion

Referring to the A vs H plot in Figures 3b and d, the latter is selected as the final design due to the smaller total heat exchanger area required. To verify the results obtained, the annualised capital and utility costs are calculated for both retrofit options using Eq(3) and the annualised utility cost listed in Table 1. Table 2 compares the heat recovery and economic performance of the retrofit design before and after area minimisation.

$$Annualised\ capital\ cost = Annualised\ factor \times (1{,}300 + 1{,}000A^{0.83}) \quad (3)$$

where the annualised factor is 0.322.
Results of this study show that the new graphical approach can guide user to minimise the heat exchanger area of a retrofit design and reduce its capital and utility costs. After identifying the heat exchangers with large area, adjustment can be made directly using STEP diagram to reduce the heat exchanger area. The heat recovery performance is maintained in this case study as the adjustment only involved altering the stream pair at the end of the stream. It is proven that the new graphical approach enables user to screen the more economically feasible retrofit option without the need to calculate the cost required.

Table 1: Annualised cost of utilities and their supply and target temperatures

Utilities	Supply temperature (°C)	Supply temperature (°C)	Annualised cost ($/kW.y)
High pressure steam	255	254	70
Cold water	40	30	10
Cooling Air	65	40	5

Table 2: Comparison of results

	Before area minimisation	After area minimisation
Number of additional units	5	5
Cold utility (kW)	1,000	1,000
Hot utility (kW)	750	750
Total additional heat exchanger area (m^2)	544	525
Annualised capital cost ($/y)	67,281	65,942
Annualised utility cost ($/y)	62,500	59,500
Annualised total cost ($/y)	129,781	125,442

4. Conclusion

A new graphical approach for HEN retrofit which consists of the STEP diagram and the A vs H plot is proposed for capital and utility costs minimisation. The new approach can graphically guide users to identify large and potentially costly heat exchangers in the retrofit design, and to minimise the heat exchanger area prior to performing economic analysis.

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