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Comparison of Graphical Tools for Targeting and Retrofit of Heat Exchanger Networks

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Depleting fossil and water resources, increasing environmental concerns and energy prices provide the impetus to continually improve heat integration in existing process plants. Four new graphical tools with potential to guide Heat Exchanger Network (HEN) design and retrofit are reported in literatures since 2010. These tools include Stream Temperature vs Enthalpy Plot (STEP) and HEat Allocation and Targeting (HEAT) for simultaneously targeting and design of a HEN, Energy Transfer Diagram (ETD) to capture the flowrate of heat transferred from the heating utilities to the environment through each heat-exchanger and process units as a function of temperature, Heat Exchanger Load Diagram (HELD) to identify heat-exchanger configuration. All these graphical tools are concisely explained and applied to guide the design and retrofit of a HEN problem. Compared with the traditional Composite Curve (CC) and Grid Diagram (GD), the advantages and disadvantages of each tool are compared and summarized. Suggestions to make a choice are provided.

1. Introduction

The statistical annual report on national economic and social development in 2018 of P.R. China released that the total energy consumption in 2018 was 4.64 x10^9 tons of standard coal equivalents, increased by 3.3% compared to that in 2017. The consumption of coal accounted for 59%, while that of clean energy resources like natural gas, water power, wind, nuclear and etc. accounted for 22.1%. The energy consumption per National GDP of 10,000 Yuan decreased by 3.1% compared to that in 2017(National Bureau of Statistics of China, 2019). In addition, the efficiency of energy utilization was continuously improved although the amplitude of improvement was decreasing. Note that ever improving energy efficiency contributes most to the emission reduction of worldwide greenhouse gases and promotes the economic and social development in a fast way.
As one of the major energy consumers, process industries strive to improve the efficiency of energy utilization through energy integration which is believed to be the most effective way to save both hot and cold utility consumption. Graphical methods consisting of a targeting stage and a design stage have been widely used in heat integration (Nordman and Berntsson, 2009). These methods are characterized by insightful graphical tools are adopted to predict the design or retrofit target before the design stage. Grand Composite curves (GCCs) and grid diagram (GD) have been the most popular graphical tools for designing optimal HEN (Kemp, 2007) and are regarded as the benchmarks of comparison. Reported graphical methods include STEP method (Wan Alwi and Manan, 2010), Network pinch approach (Bakhtiari and Bedard, 2013), Advanced Composite Curves (ACCs) based method (Nordman and Berntsson, 2009), Extended Grid Diagram method (Yong et al., 2015), Energy Transfer Diagram (ETD) based method (Bonhivers et al., 2019) and Gadalla's new graphical method (Gadalla, 2015). Only STEP and ETD methods are succinctly explained here because of the limit on paper length.
Stream Temperature vs. Enthalpy Plot (STEP) is a graphic tool for simultaneous targeting and design of a HEN, which is constructed on individual streams rather than Composite Curves (Wan Alwi and Manan, 2010). Heat Allocation and Targeting (HEAT) diagram companies with STEP temperature and enthalpy and represents the corresponding topology of HEN. Recently, STEP tool is extended for HEN retrofit (Lai et al. 2018b), each existing exchanger including cooler and heater is sequentially represented on the temperature versus enthalpy plot and four heuristics are adopted to guide the retrofit procedure after the pinch is identified by other Pinch design method, so STEP tool for HEN retrofit is more appropriately termed as Exchanger STEP (ESTEP).

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Energy Transfer Diagram (ETD) was developed to capture the flowrate of heat transfer from the heating utilities to the environment through each heat exchanger and process operation as a function of temperature (Bonhivers et al., 2014a), this diagram can be used to identify modifications of the HEN and the process operations to save energy with the help of Bridge Analysis (BA). A set of matches connecting heat outlets to hot utility users is termed as "bridge", a comparison among the GCC, ACC and ETD for analysis of the HEN of a Kraft pulp mill showed that the information provided by these approaches was consistent; however, the level of detail progressively increased from the GCC to the ACC until the ETD (Bonhivers et al., 2014b). To build the connection between ETD and conventional Pinch Analysis (PA) tools, such as GCC, Modified Energy Transfer Diagram (METD) is developed by Lal et al.(2018a), this new tool allows the identification and qualification of retrofit bridges and use colour to provide more insights into the retrofit problem.
Note that above mentioned graphical methods make their respective contributions to gain insights and guide the design or retrofit of HEN. A puzzle would appear when a choice on these tools should be made. This paper presents critical comparisons of STEP and ETD with GCC, the merits and demerits of these two graphical methods are illustrated and summarized.

2. STEP method

2.1 Concepts of STEP and HEAT

STEP is developed to simultaneous targeting and design of a HEN and overcomes the key limitations of the CCs and the GD (Wan Alwi and Manan, 2010). The profiles of continuous individual hot and cold streams are mapped on a shifted temperature versus enthalpy diagram in the STEP which simultaneously locates the pinch points, shows the energy targets and the Maximum Heat Allocation (MHA). MHA can be graphically converted to a Maximum Energy Recovery (MER) network and represented on a HEAT diagram based on STEP temperature and enthalpy.

2.2 Illustration of STEP and HEAT

Example 1 (Linnhoff and Flower, 1978) is adopted to illustrate main characters of STEP and HEAT, its stream data is provided in Table 1. The minimum temperature approach (ΔT_{min}) is assumed to be 10 °C in this example.

Table 1: Steam Data of Example 1

stream	Ts(°C)	Tt(°C)	FCp(kW/°C)	ΔH(kW)	Shifted Ts(°C)	Shifted Tt(°C)
H1	180	40	2	-240	175	35
H2	150	40	4	-440	145	35
C1	60	180	3	360	65	185
C2	30	105	2.6	195	35	110

Note that the shifted temperature of hot stream in Table 1 is obtained by subtracting $\Delta T_{min}/2$ from its original value while the shifted temperature of cold stream is gotten by adding $\Delta T_{min}/2$ to its original value. Figure 1

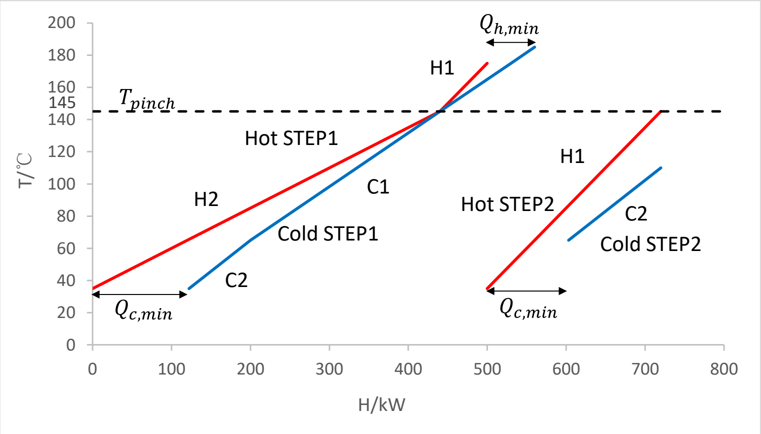

Figure 1: Shifted STEP showing pinch and the minimum utility targets for Example 1

is the shifted STEP of Example 1; interested readers are referred to Wan Alwi and Manan (2010)'s work for the detailed steps on how to construct this diagram. From this figure, the pinch temperature can be determined as

145 °C (shifted temperature), the minimum hot utility consumption is $Q_{H,min} = 60$ kW and cold utility consumption is $Q_{c,min} = 125 + 100 = 225$ kW. These targets and the pinch temperature match those obtained using CCs (Kemp, 2007).
The STEP shows not only utility targets and pinch temperatures, but also how the individual hot and cold streams should be matched to achieve these targets. These required matches from the STEP can now be graphically translated into a MER network design and represented on a HEAT diagram (Wan Alwi and Manan, 2010). The HEAT of Example 1 is provided in Figure 2a in which a heat exchange matching between a hot and a cold stream is represented by a pair of rectangular boxes with a line linking the hot and the cold stream. The width of the box represents the amount of heat exchange. Note that the procedure to construct a HEAT diagram from STEP is described elsewhere (Wan Alwi and Manan, 2010).

2.3 Comments on STEP and HEAT

2.3.1 Contributions of STEP and HEAT

STEP is a visualization tool which shows the MHA based on individual hot and cold streams rather than CCs, and MHA can be graphical converted into MER network. In addition, HEAT can substitute GD and reduces the routine HEN design tasks such as streams enthalpy balances, and temperature feasibility checking associated with CCs and GD. Furthermore, STEP provides a systematic and robotic procedure to obtain a MER network while pinch principles and designer’s expertise were heavily relied when CCs and GD were adopted for HEN design.

2.3.2 Limitations of STEP

Just as Wan Alwi and Manan(2010) themselves acknowledged that STEP might not be effective to manually handle complex problem involving more than 10 streams because STEP and HEAT would be tedious to draw manually by then. Furthermore, it is the strict procedure of STEP and HEAT construction that guarantee a MER network to be obtained, such a MER network usually is featured by more heat exchanger units and further evolutions are needed to break loops or path relaxations to reduce capital costs. More importantly, the STEP is designed to obtain on MER network only, the cases where multiple MER networks exist are not considered. For example, Example 1 has three more MER networks shown in Figure 2b which cannot be found by STEP method.

2.4 ESTEP for HEN retrofit

Lai et al.(2018b) extended the STEP method for HEN retrofit. Comparing with STEP method for HEN synthesis, the focus of ESTEP is changed from continuous individual hot and cold stream into each individual exchanger including heater and cooler, which results in that the pinch and utility targets cannot be predicted and other Pinch design methods, such as Problem Table Algorithm(PTA) or the CC, are relied to fulfill this task. In addition, 4 heuristics are adopted to generate retrofit network after those cross-pinch matches are identified and removed. So, the ESTEP is rule-based on the retrofit stage and experience plays an important role in the retrofit procedure.

3. ETD and HELD tools

3.1 The concept of ETD and HELD

Energy Transfer Diagram (ETD) was developed to capture the flow rate of heat transferred from the heating utilities to the environment through each heat exchanger and process operation as a function of temperature (Bonhives, et al., 2014a). It can be used to identify heat saving modifications of a HEN. Heat-exchanger Load Diagram (HELD) can be used for the design of new HEN or in retrofit (Bonhives, et al., 2017b). It represents thermodynamic constraints corresponding to heat transfer. In HELD, the ordinate axis represents heat load while the abscissa represents temperature, plot the heat load of sources and sinks as a function of temperature and move these curves vertically such that each heat supplier is placed at a higher temperature than that of its receptor.

3.2 The usage of ETD and HELD

Example 2 from (Bonhives, et al., 2017a) is used to illustrate the usage of ETD and HELD. The stream data is provided in Table 2 and the existing network is shown in Figure 3a (the heat load of each exchanger in kW is notated). The ΔT_{min} after retrofit is assumed to be 10 °C.

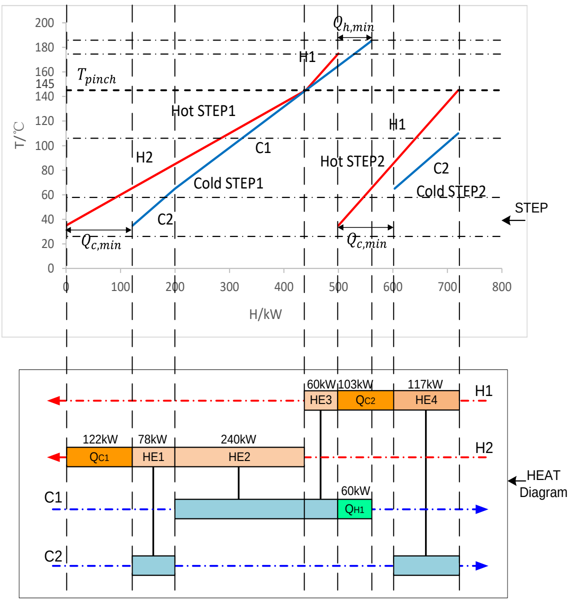

Figure 2a: HEAT diagram of Example 1

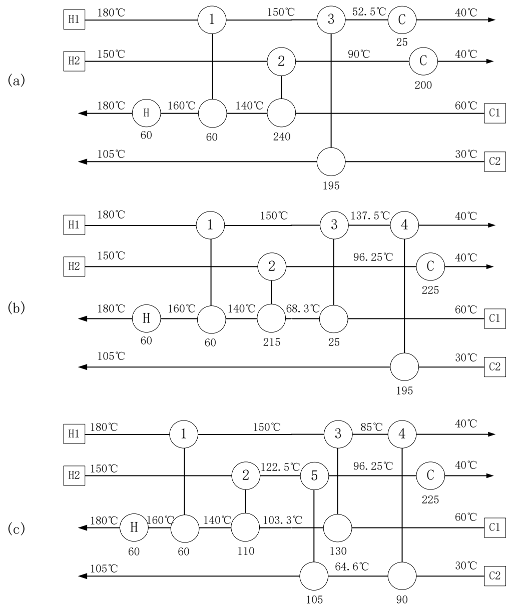

Figure 2b: Alternative MER networks of Example 1

Table 2: Steam Data of Example 2

stream	T_s(°C)	T_t(°C)	FCp(kW/°C)	ΔH(kW)	Shifted T_s(°C)	Shifted T_t(°C)
Ha	125	65	40	-2400	120	60
Hb	175	45	10	-1300	170	40
Ca	40	112	15	1080	45	117
Cb	20	155	20	2700	25	160

3.2.1 The construction of ETD

In ETD, the ordinate axis represents the flow rate of energy transferred, and the abscissa represents the temperature range between the heating utilities and the environment. The diagram shows the degradation of heat through each existing heat exchanger and process operation. The energy transfer curve of an existing heat exchanger or heater or cooler represents the flow rate of heat transferred as a function of temperature; such curve is evaluated for each existing heat exchanger. Note that all temperature should be shifted just the same as in section 2.2. All the curves are then stacked (summation of individual curves). Note that the top curve is called “network curve” and represents the total flow rate of heat cascaded through the network. The

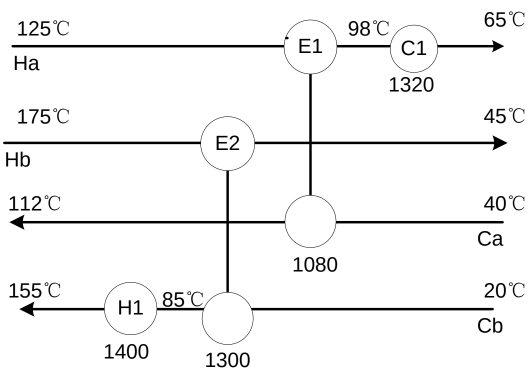

Figure 3a: The existing HEN of Example 2

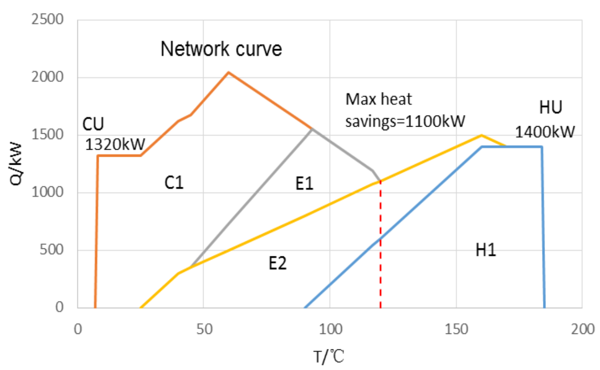

Figure 3b: The ETD of Example 2

maximum heat savings achievable without any connection constraint is equal to the minimum value of the network curve, and the pinch temperature is just the corresponding abscissa value of the minimum value of the network curve. Figure 3b shows the shifted pinch temperature is 120 °C and the maximum heat savings achievable is 1100 kW. If traditional Pinch Design Method is adopted, the same pinch temperature can be found and the minimum hot utility is 300 kW and the minimum cold utility is 220 kW which are just conform to the results shown in Figure 3b.

3.2.2 The construction of HELD

It is suggested that place the cold utility in the bottom and start at Q =0 kW as shown in Figure 4. Sort all cold streams or sinks according to their target temperatures in ascending order and form a que, and then plot the first sink in the que that begin from the cumulative ΔQ of the cold utility (this value is 1320 kW in Example 2) , repeat this step till the last cold stream in the que is plotted. The hot utility and hot streams can be easily plotted based on the current network topology after the positions of their matching cold streams are fixed as shown in Figure 4.

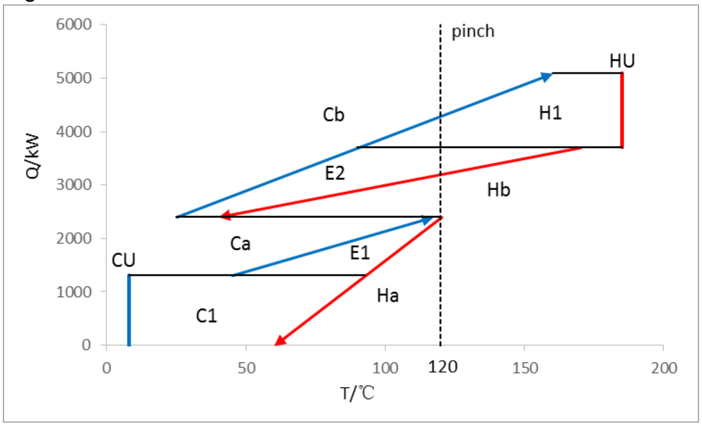

Figure 6: The HELD of existing network of Example 2

3.2.3 The contributions of ETD and HELD

Comparing with CCs, ETD can predict the maximum energy saving and those heat exchangers crossing the pinch based on the existing HEN configuration and selected ΔT_{min} for retrofit. For example, E2 and H1 in Figure 3b are transferring heat across the pinch of 120 °C (shifted value). Because temperature and heat load are the abscissa and the ordinate axis of HELD respectively, HEN modifications can be visualized on this diagram by vertical shifts of sources, In addition, HELD can be used as a visual tool independently. Comparing with GD, HELD intuitively represents the distribution of driving force of heat transfer in each exchanger, and a designer can shift the source lines freely to find feasible retrofit options as long as the driving force is not less than zero. So HELD is more helpful and intuitive than GD in guiding HEN retrofit.

4. Discussion

The comparison of above mentioned seven graphical tools for HEN design or retrofit is summarized in Table 3.

Table 3: comparison of seven graphical tools

Order	Features	CCs	GD	STEP	ESTEP	HEAT	ETD	HELD
1	Shifted temperature is required ?	No	No	Yes	Yes	Yes	Yes	No
2	Predict the pinch and energy target?	Yes	No	Yes	No	No	Yes	No
3	Predict the match relation of individual streams?	No	Yes	Yes	Yes	Yes	Yes	Yes
4	Show heat load of exchangers?	No	Yes	Yes	Yes	Yes	No	Yes
5	Show the driving force of heat transfer?	No	No	Yes	Yes	No	No	Yes
6	Show crossing pinch exchangers?	No	Yes	Yes	Yes	No	Yes	Yes
7	Avoid heat balance calculation and temperature feasibility check?	-	No	Yes	Yes	Yes	-	Yes
8	An independent graphical tool?	Yes	Yes	Yes	Yes	No	Yes	Yes

* - denotes not available

5. Conclusions

Popular Pinch Design method characterized by CCs and GD lacks specific method to guide the synthesis of HEN after the pinch and energy targets are predicted. Instead, only pinch principles and heuristics are available on the second stage of HEN design. STEP overcomes this limitation, it provides specific procedure to simultaneously targeting and design HEN, and a feasible MER network is guaranteed to be found. The side effect of STEP is that other alternative MER networks are lost. HEAT companies STEP to graphically convert MHA to a MER network and avoid the routine HEN design tasks such as stream enthalpy balances and temperature feasibility checking. ESTEP can handle HEN retrofit and is heuristics-based approach after the retrofit targets are determined by other PA methods. ETD and HELD are developed for HEN retrofit only and existing HEN topology is the start point of these two graphical tools. HELD can be independently used as an important visualized tool to guide the HEN retrofit.

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