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A Graphical Method for Simultaneous Targeting and Design of Multiple Utility Systems

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Utility targeting as well as optimal placement are among the key steps in the design of a cost-effective process utility system. Composite Curves, Grand Composite Curves (GCC) and Balanced Composite Curves are the established graphical tools for targeting and optimal placement of multiple utilities based on the Pinch Analysis technique. Although the composite graphical tools can provide valuable graphical insights and yield acceptable utility targets in terms of loads and levels, they could not pinpoint the exact heat recovery matches between process and utility streams. As a result, these composite graphical tools could not be used to perform heat allocation between the process and the individual utility streams, and for targeting the process-utility surface area targets. This paper presents an extended Stream Temperature versus Enthalpy Plot (STEP) method that is used to simultaneously target the multiple utilities and perform heat allocation between the utilities and the individual process streams. Due to the composite nature of the GCC, targeting involving variable-temperature utilities can yield inaccurate results. A case study has been used to demonstrate how this limitation can be overcome by using the extended STEP method.

1. Introduction

Pinch Analysis has gained worldwide acceptance as an effective and reliable method to design a maximum energy recovery network for industrial processes. One of the most famous graphical tool in Pinch Analysis is the Temperature-Enthalpy (T-H) diagram known as the Composite Curves (CCs) that was introduced by Linnhoff et al. (1982). The hot (or cold) CCs is constructed by compositing a set of hot (or cold) streams that exist within a given temperature range. The hot and cold CCs are then shifted towards one another along the enthalpy (H) axis until they are pinched to obtain the maximum energy recovery potential and the minimum heating and cooling targets. In order to design a system with multiple utility levels, the Grand Composite Curve (GCC) was introduced by Townsend and Linnhoff (1983). The GCC is also a Temperature-Enthalpy (T-H) diagram. However, the x-axis (enthalpy axis) represents the horizontal distance between the shifted hot and cold CCs. Another alternative is to use the problem heat cascade data from the Problem Table Algorithm by Linnhoff and Flower (1978). Utility lines which represent the utility temperature are then drawn on the GCC starting from the cheapest to the more expensive utilities. The point where the utility line touches the GCC is termed as the “Utility Pinch”. The utility line can have a constant temperature (e.g. steam) or variable temperature (e.g. hot oil and cooling water). The Utility Pinch cannot be located by using the GCC when the level of a placed utility is between the temperatures of a heat recovery pocket. In this case, the Balanced Composite Curves (BCCs) are used. BCC was introduced by Mcmullan et al. (1987). The BCC is particularly useful to show the effect of multiple utilities, multiple pinches on temperature driving force in the network, thus revealing constraints on network design more clearly. Balanced Grid diagram is another graphical tool proposed in this work.

Utility targeting for systems including flue gas and air preheat was presented by Hall and Linnhoff (1994). The work shows the effect of variation of air flow rate on flue gas targeting and eventually fuel consumption. Different furnace targeting approaches were explained and their limitations were highlighted. The GCC was selected as a more accurate graphical tool for furnace targeting, but it was also pointed out that since utility and process streams are combined in one GCC, some vital individual stream’s information

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can be lost. Therefore, the Utility Grand Composite Curves (UGCC) is presented to give the designer a better understanding of the process/utility system's interface. Utility streams are presented as a single curve, completely separated from the traditional process GCC. The UGCC is a plot of the (negative) enthalpy difference between utility composites.
Another graphical approach was proposed by Marechal and Kalitventzeff (1996) called the integrated CCs to evaluate the integration of utility system. They divided utilities into two sub-groups: the primary utilities such as water, fuels and air and the secondary utilities being used for energy transfer and transformation i.e. steam networks and refrigeration. The authors tried to find the optimum utility system by using the pinch technology as well as mathematical approaches. Also, the aim was to satisfy all the energy demanded by process at the minimum cost, based on three steps approach named AGE (Analysis, Generate, and Evaluate). In the analysis step, pinch technology helps designers to find the minimum energy requirement. The optimum flow rate for utilities is calculated by Mixed Integer Linear Programming (MILP) approach. The new graphical technique proposed in this paper was used to evaluate the integration of the utilities and process streams.
Lakshmanan and Fraga (1997) addressed a case when there is no process stream within an interval; therefore the composite line is not continued. For this case, Problem Table Algorithm cannot represent the gap in the Composite Curves. Furthermore, they represent the same cases in Composite Curves where Pinch rules cannot be applied. This paper explains the limitation of Pinch Technology as well as Problem Table Algorithm (PTA). They identified the "critical point" as the point where any reduction of ΔT_{min} will not maximize energy recovery.
Multiple utility targeting for heat exchanger network was presented by Shenoy et al. (1998). Their work extends the supertargeting approach based on the Cheapest Utility Principle (CUP). The main concept is to increase the total utility consumption while the amounts of expensive utilities remain constant. The capital cost was considered simultaneously with utility cost. Hall et al. (1982) considered both the energy and capital cost in selecting and optimizing the utility requirement in order to target the overall minimum cost of heat exchanger network. However, their method of determining the global optimum ΔT_{min} may not necessarily yield an acceptable target. It was suggested that since the Total Annual Cost (TAC) curves are almost flat near to the optimum ΔT_{min}, it would be more beneficial to use the optimal ΔT_{min} range instead of single optimum ΔT_{min}. The paper also provided an ability to eliminate small utility units by accepting a small TAC penalty in some cases. The optimum lead distribution (OLD) plots are another approach introduced in this work. The OLD is a graphical tool to show the optimum utility load within the optimum ΔT_{min} range.
Jezowski and Jezowska (2002) presented a graphical approach to visualise the minimum cost at the minimum flow rate of non-point utilities (cooling water, hot oil and hot gas from a furnace). Note that the price of utility has direct connection with its temperature. For hot utilities; the utility at higher temperature has higher price. The opposite is true for cold utilities. This paper provides new insights on restricting outlet temperatures of utilities to guarantee heat recovery with minimum flow rates of utilities. The amount of energy penalty due to the use of utility flow rate higher than the minimum flow rate obtained by utility limitation profile (ULP) can be determined by using the GCC. The represented methodology does not require mathematical calculations. The amount of energy loss and the outlet temperature as well as the flow rate limitations can be seen from the GCC.
Castier (2007) presented new rules for utility targeting. This model is based on a direct extension of the Problem Table Algorithm (PTA). In this method, the minimum hot and cold utility consumptions at any temperature interval can be determined solely via an algorithmic method. The advantage of this method is that it minimises the utility cost through the appropriate placement of hot and cold utilities.
Salama (2009) developed a new technique called the enthalpy flowrate technique for the construction of heat exchanger network composite curves by using stream cumulative enthalpy flowrate as the independent variable. The enthalpy flow rate technique allows the constructions of newly introduced curve termed as Complement Grand Composite Curves (CGCC). The CGCC is considered a valuable tool for (a) presentation of the temperature differential distribution between the composite curves (CCs), (b) estimation of heat exchanger (HEX) area, and (c) facilitation of HEX area estimation in multiple –utility targeting. The cumulative enthalpy flowrate and temperature technique provide a full range of information about the CCs and presents the GCC and CGCC information in a single graph, which can assist the HEN designer during the targeting and design stages.
Wan Alwi and Manan (2010) introduced a new graphical method for simultaneous targeting and design of heat exchanger networks. The Stream Temperature versus Enthalpy Plots (STEP) presented by the authors represent profiles of continuous individual cold and hot streams being plotted on a shifted temperature versus enthalpy diagram. Energy targets, pinch points and maximum heat allocation (MHA) are shown simultaneously by STEP. The proposed graphical tool (STEP) can eliminate limitations of Composite Curves (CCs) as well as the Grid Diagram. The HEat Allocation and Targeting (HEAT) diagram

was used alongside STEP to graphically perform the maximum heat allocation (MHA) and generate the maximum energy recovery (MER) network. The HEAT diagram eliminates the need for enthalpy balance calculations as well as temperature feasibility checking that are required in other HEN design techniques. Techniques for targeting the multiple utilities and minimum network area using STEP were also described in the paper.

Sun et al. (2013) extended the STEP method for cost targeting that considered different types of heat exchangers. The method improved the total cost target and allowed a more accurate minimum temperature difference, ΔT_{min} to be determined. Walmsley et al. (2013) later presented a Cost Derivative Method (CDM) to find the optimal area allocation for a defined Heat Exchanger Network (HEN) structure and stream data. The method eliminates the need for stream splits to achieve minimum total cost. The authors introduced the utility cost savings "flow-on" factor, θ to evaluate the downstream effects of utility use and cost as a result of changes in the area of one exchanger. Our review shows that the GCC and BCC remain as the most predominant and widely used tool for multiple utility targeting due to their relative simplicity and easy of use. These tools have been featured even in the recent Process Integration books such as the ones by Kemp (2007), and more recently Klemeš (2011). In this paper, limitations of using the GCC in multiple utility targeting, especially for cases involving variable-temperature utilities are highlighted. The method based on the STEP technique has been proposed to overcome this limitation.

2. Limitation of the GCC for Targeting Involving Variable-Temperature Utilities

The GCC is a profile of the net heat surpluses and demands of process streams at different ranges of shifted temperature intervals of a process. It is essentially a profile of the collective or composite streams, as opposed to individual streams. In multiple utility targeting, the minimum heat capacity flowrates (FCp_{min}) of the variable-temperature utilities such as flue gas (FG) and cooling water (CW), have been determined by matching these utilities against the GCC. In doing so, the FCP_{min} can either be limited by the pinch point (Figure 1a) or the heat recovery "pocket" (Figure 1b) of the GCC. As will be proven next, targeting the FCp_{min} by matching the variable-temperature utility with the composite GCC profile can yield inaccurate results. Example 1 is used to illustrate this case. Table 1 represents the stream data, and Figure 2 the GCC for Example 1. The shifted process pinch temperature is 235 ^oC, Q_{Hmin} is 680 kW and Q_{Cmin} is 485 kW (see Figure 2). The FG shifted target temperature (T^*_t) is determined as 236.5 ^oC and its FCp_{min} is 4.290 kW/^oC (obtained from the flue gas line slope).

A simple way to check the accuracy of these targeted values is by including the FG and its targeted values as part of the process stream data. These values are then used to plot the Composite Curves. If the FG values of T_s = 400 ^oC, T_t = 241.5 ^oC and FCp_{min} = 4.290 kW/^oC are correct, a Q_{Hmin} of 0 kW should be obtained, with the Q_{Cmin} and shifted Process Pinch temperature unchanged. However, the Composite Curves that include the targeted FG stream gives a new Q_{Hmin} of 0.035 kW. The Q_{Cmin} and the pinch point remain unchanged. This proves that, utility targeting using the GCC for cases involving variable-temperature utilities can yield the wrong results. This discrepancy has been caused by the FG stream being matched with a "pseudo single" demand stream that is essentially a composite, as opposed to an individual stream (see Figure 2). The STEP method, on the other hand shows that the FG stream should be matched with two demand streams as opposed to one, thereby resulting in a different average FCP_{min} for the FG stream.

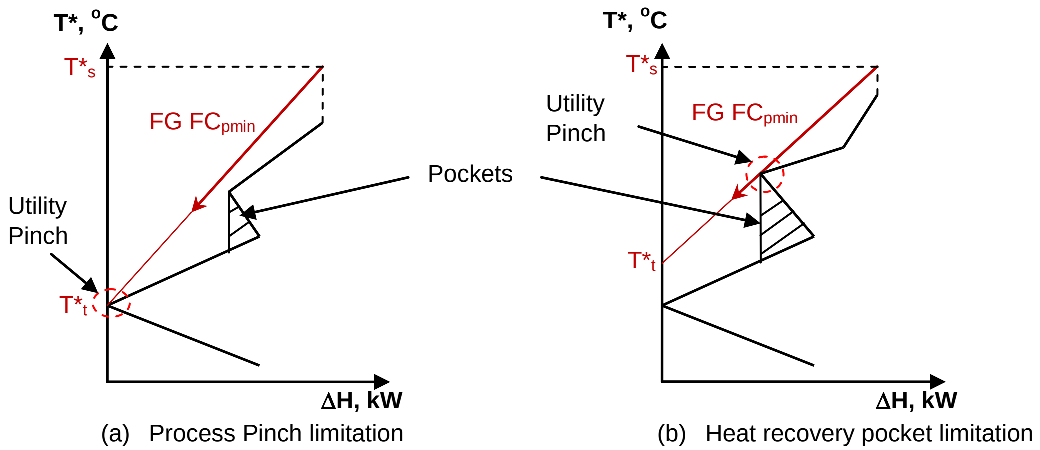

Figure 1: Determining the FCp_{min} for the variable temperature utility using the GCC

Table 1: Stream data for Example 1, ΔT_{min} = 10 ˚C

Stream	Supply Temperature, Ts (^oC)	Target Temperature, Tt (^oC)	Heat capacity flow rate, FCp (kW/^oC)	Enthalpy, ΔH (kW)
H1	330	260	2	-140
H2	280	150	3	-390
H3	260	120	7	-980
FG	400		To be determined	
C1	165	320	5	775
C2	115	165	6	300
C3	230	300	9	630
CW	25	35	To be determined	

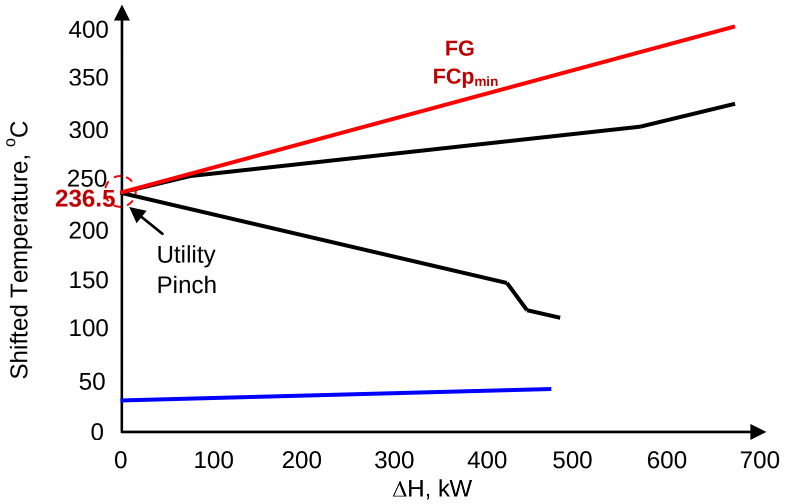

Figure 2: FCp$_{min}$ determination by using GCC for Example 1

3. Methodology

The STEP method introduced by Wan Alwi and Manan (2010) has been used for targeting constant-temperature multiple utilities. This section describes the extension of STEP method for multiple utility targeting involving variable-temperature utilities. STEP allows both the targeting and network design to be done simultaneously by considering the utility as well as process streams as individual, as opposed to composite streams. The step-wise procedure for variable-temperature utility targeting is described below. Further details and examples of STEP construction is described in Wan Alwi and Manan (2010).

1. Step 1. Construct the STEPs using the stream data from Example 1. Referring to Figure 3 for example, construction of the STEP 1 and STEP 2 profiles should begin with the stream having the biggest FCp (to form STEP 1), to the one having the lowest FCp (to form STEP 2 and the rest). The first hot STEP (hot STEP 1) is obtained by plotting the continuous profile of individual hot streams with the biggest FCp, throughout the available range of shifted interval temperatures. Hot Step 2 is constructed from hot streams with the next biggest FCp. The cold STEPs are constructed in the same manner.
2. Step 2. Determine the pinch temperature and energy targets. This is done by shifting the cold STEP 1 towards the hot STEP 1, and the cold STEP 2 towards the hot STEP 2, until the pair of curves pinch. For example 1, the Q_{Hmin} is 680 kW, the Q_{Cmin} is 485 kW and the shifted process pinch temperature is 235 ^oC.
3. Step 3. Determine the variable-temperature utility endpoint, or the “temperature limiting point (TLP)”. Note from Figure 3 that the overshoot of the cold STEP 1 represents a heat sink that needs to be heated by a heat source, either from a hot process stream, or a hot utility. The flue gas (FG) is the only heat source available for this purpose. The FG segment above the interval temperature of 310 ^oC is used to safisfy the heat sink of cold STEP 1, while the FG between 310 and 253 ^oC is used to satisfy the heat sink for cold STEP 2. The lowest FG temperature of 253 ^oC therefore represents the

TLP (see Figure 3). Note that, if the TLP is lower than the acid dew point temperature (ADT), the ADT will be chosen as the TLP.

4. The FCp_{min} is determined by dividing the Q_{Hmin} with the flue gas temperature difference (Ts = 400 ^oC and Tt = 258 ^oC). This gives FCp_{min} of 4.789 kW/^oC.

Checking the targeted flue gas values by using Composite Curves gives Q_{Hmin}, Q_{Cmin} and shifted Process Pinch temperature of 0 kW, 485 kW and 235 ^oC. The preceding analysis shows that extended STEP method can yield the accurate FCp_{min} target for the case of variable-temperature utilities.

5. Since the process streams are individual, as opposed to composite streams (in the case of GCC) the available heat from the targeted flue gas stream can now be allocated to the relevant cold STEPs as shown in Figure 3.
6. The heat transfer area that results from the pairing of the utility and the cold STEP can then be calculated.

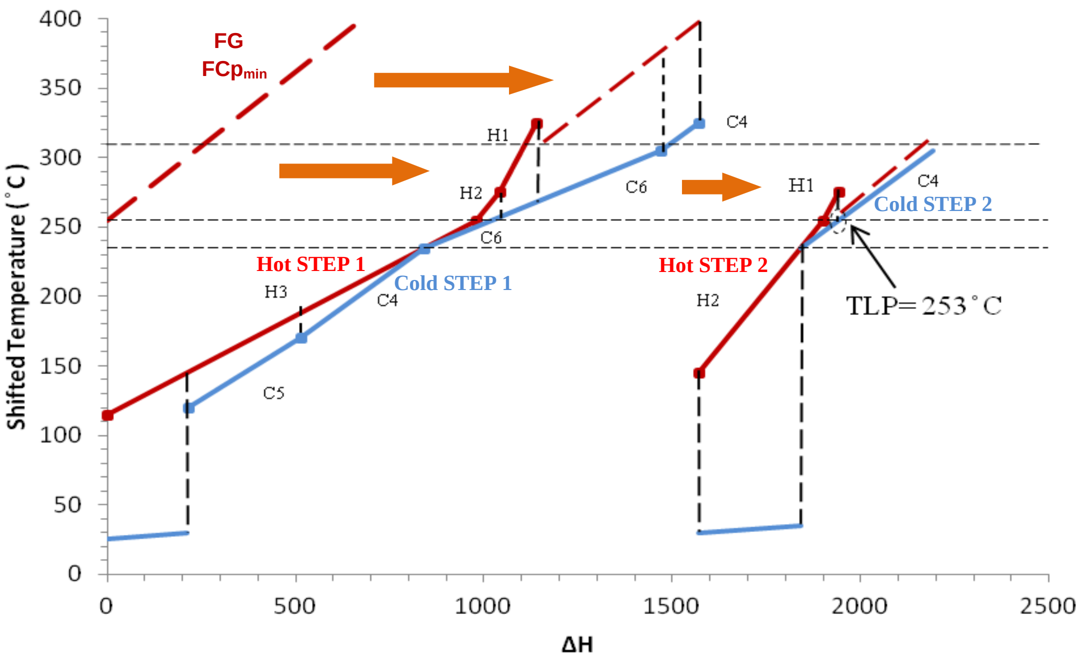

Figure 3: STEP with variable-temperature utility FCp_{min} targeting

4. Conclusions

The GCC method for targeting of variable-temperature utilities yields inaccurate results because the procedure involves matching a utility stream with a composite demand stream. GCC also cannot be used to perform heat allocation between the individual utility and process streams. An extended STEP method has been used to overcome these limitations. Application of the new STEP method on a case study has yielded the accurate variable-temperature utility targets. Work is in progress to further extend the STEP method for targeting the minimum HEN area considering variable-temperature utilities.

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