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A New Graphical Method for Heat Exchanger Network Design Involving Phase Changes

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Heat Exchanger Network Synthesis (HENS) plays a major role for effective energy integration in chemical process plants. In HENS, several hot and cold streams and utilities with specific inlet and desired outlet temperatures are involved. Stream Temperature versus Enthalpy Plot (STEP) is new graphical tool which can complement Composite Curves (CCs) and Grid Diagram (GD) by representing individual, as opposed to composite streams on temperature versus enthalpy diagram, and by allowing designers to perform targeting and network design simultaneously. Previous researches do not consider the effect of phase changes in the hot and cold streams and assume constant specific heat capacity, Cp along process streams. The aim of this study is to propose a new graphical method for HENS targeting and network design involving phase changes. Using an illustrative example, STEP procedure is proposed for the determination of minimum utility targets with the minimum number of heat exchangers. Results of the analysis using the modified STEP is compared with those obtained using Composite Curves. It is found that the modified STEP provides more accurate and realistic results and allows the selection of different types of heat exchangers.

1. Introduction

Heat Exchanger Network Synthesis (HENS) has been one of the key areas of research that has significantly contributed to industrial energy efficiency improvements over more than four decades. HENS include the development of Heat Exchanger Network (HEN), heaters and coolers with minimum annualised cost by considering several key design criteria (Pintaric and Kravanja, 2015). Two categories of methodologies that have been proposed for HENS include sequential approach and simultaneous approach (Mian et al., 2016). The well-known examples of sequential approach are Pinch Analysis by Linnhoff and Hindmarsh (1983), mathematical programming techniques by Cerda et al. (1983) and the transshipment problem formulation by Papoulias and Grossmann (1983). Simultaneous approach involves the simultaneous synthesis technique for HENS by using mixed integer nonlinear programming (MINLP) as proposed by Yee and Grossmann (1990).
In Pinch Analysis, the use of Composite Curves (CCs) proposed by Hohmann (1971) are the most common graphical approach for maximum energy recovery targeting followed by network design by using the Grid Diagram (GD) and Pinch Design Method (PDM) by Linnhoff and Hindmarsh (1983). CCs have some limitations as they represent composites temperature-enthalpy plot instead of individual streams (Bonhivers et al., 2014). As a result, they cannot completely map individual hot and cold streams, and process and utility streams. The limitation of GD and PDM is that, they do not follow any temperature or enthalpy scale and hence, they require designers to supply or calculate streams temperature and enthalpies, to perform heat balance and to verify temperature feasibility during HENS (Wan Alwi and Manan, 2010). In order to overcome the limitations of CCs and GD, Stream Temperature versus Enthalpy Plot (STEP) was proposed by Wan Alwi and Manan (2010) as a graphical tool for HENS. The individual process stream may be present in more than one set of continuous STEPs.

Most of the previous researchers do not consider phase changes during heat exchange and assume constant heat capacity along each stream. The effects of phase changes on HENS have been studied by a few researchers over the last two decades. Castier and Queiroz (2002) introduced a Pinch-based approach for the energy targeting problem with multi-component phase changes. Liporace et al. (2004) included this method into the sequential HENS approach. Ponce-Ortega et al. (2008) extended the MINLP model of Yee and Grossmann (1990) to tackle isothermal phase changes. Hasan et al. (2008) modelled multi-component phase changes using a separate, nonlinear, empirical correlation for each zone (liquid, gas, 2-phase) of a temperature-enthalpy curve. Hasan et al. (2010) proposed a mixed-integer nonlinear programming formulation and a solution algorithm to incorporate non-isothermal phase changes in HENS. Recently, a new graphical method proposed by Gadalla (2015) for heat recovery analysis system to analyse energy performance with respect to the energy targets in HEN retrofit. To date, there has not been a graphical method that can be effectively used for targeting and design of HEN involving phase changes. This study aims to develop a new graphical method for simultaneous targeting and HEN design involving phase changes.

2. Methodology

This section describes the development of the modified STEP as the new graphical method for HEN targeting and design involving phase changes. The stepwise procedure to construct the modified STEP is discussed next using an illustrative example.

2.1 Step 1: Data Extraction

The first step is the extraction of the heat and mass balance data for all process streams that are involved in heat exchange. The extracted data include flow rates, F, supply temperatures, T_s, and target temperatures, T_t of all the process streams. For isothermal phase change, the boiling point temperature, T_b and specific heat of vaporisation, ΔH_v for each process stream should be extracted. The bubble points (BP) and dew points (DP) of process streams are extracted for non-isothermal phase change because the phase change of multi-component stream occurs at the temperature interval from BP to DP. In the second stage of data extraction, the process streams involving phase change are identified by referring to T_b of each process stream. Sub-streams can be defined as the division of the original stream with T_b as boundary. Next, the phases, specific heat capacity, Cp, pressure, P, and heat transfer coefficient, h of all process streams and sub-streams are extracted. Calculation is needed to obtain ΔH for each process stream using Eq(1) to Eq(2). In this study, the minimum temperature difference, ΔT_{min} is assumed as 20 °C. For liquid, vapour and non-isothermal phase changing streams, the sensible enthalpy (ΔH_S) are calculated using Eq(1).

$$\Delta H_S = F \times Cp \times (T_t - T_s) \quad (1)$$

For streams involving phase change, the latent enthalpy (ΔH_L) can be calculated using Eq(2), where ΔH_v is the latent heat of vaporisation.

$$\Delta H_L = F \times \Delta H_v \quad (2)$$

2.2 Step 2: Conversion of Stream Temperatures into Shifted Temperatures

Supply and target temperatures of hot and cold streams are converted into shifted temperatures using Eq(3) and Eq(4). Shifted temperatures can be used to effectively build ΔT_{min} into the hot and cold STEPs and allow them to be matched at zero shifted ΔT_{min} and facilitate Pinch Point search during the curves construction and streams allocation (Wan Alwi and Manan, 2010).

$$T'_h = T_h - \frac{\Delta T_{min}}{2} \quad (3)$$

$$T'_c = T_c + \frac{\Delta T_{min}}{2} \quad (4)$$

2.3 Step 3: Construction of Hot and Cold STEPs

1. Calculate the average FCp of hot and cold streams that consist of sub-streams due to phase change, using Eq(5).

$$FCp_{av} = \frac{\Sigma \Delta H_{sub\ i}}{\Sigma \Delta T'_{sub\ i}} \quad (5)$$

2. Where $\Delta H_{sub\ i}$ is enthalpy of sub-stream (kW) and $\Delta T'_{sub\ i}$ is shifted temperature difference of sub-stream (°C).
3. For the construction of hot STEP, draw the individual hot streams according to their FCp_{av}. The hot streams are plotted from left to right by starting with the highest FCp_{av} stream to the lowest FCp_{av} stream. The first hot stream with the highest FCp_{av} is plotted starting with its T_t' at $H_t = 0$. The next hot stream is plotted with its H_t equal to the H_s of the previous hot stream, which means that the individual hot streams are plotted with the cumulative ΔH. H_t is defined as the enthalpy, H at T_t and H_s is defined as the H at T_s. It should be noted that FCp_{av} values are used to arrange the hot streams during construction of STEP only. The hot streams are plotted with respect to the exact value of FCp since ΔH is calculated from Eq(1).
4. Cold STEP is constructed with the procedure similar to construction of hot STEP. The only difference is the first cold stream with the highest FCp_{av} is plotted starting with its T_s' at $H_s = 0$. The next cold stream is plotted with its H_s equal to the H_t of the previous cold stream.

2.4 Step 4: Pinch Temperature Determination and Minimum Utilities Targeting

1. Start from the first cold stream on the left, shift it to match with the first hot stream on the left until Pinch Point occurs. Continue the matching until all the hot and cold streams are matched.
2. If multiple pinch problems occur, stream splitting is necessary in order to guarantee the minimum utility targeting.

2.5 Step 5: Multiple Utilities Selection and Cost Calculation

The general rule in multiple utilities targeting is to maximise the use of lower temperature hot utilities as well as higher temperature cold utilities. This is due to the cheaper costs for lower temperature hot utilities and higher temperature cold utilities. In this case study, the medium pressure steam (MPS) is the cheapest available hot utility selected. It is noted that tempered water (TW) is not selected as cold utility although it is cheaper than cooling water (CW). For this case study, the multiple utility targeting indicates that the use of TW tend to increase the number of heat exchanger, and hence increase the capital cost required. The capital cost of heat exchanger needed is estimated to be higher than the utility saving cost when TW is used as the cost of TW is only slightly cheaper than CW. TW is not selected in order to achieve minimum cost for HEN. The annual utility cost for both hot and cold utilities can be calculated by multiplying the $Q_{C,\ min}$ and $Q_{H,min}$ with the rate of utility cost.

2.6 Step 6: Minimum Area Targeting For Each Segment in STEP

Minimum area targeting for each segment in STEP is conducted based on Eq(6) and Eq(7). The log mean temperature difference (ΔT_{LMK}) is determined by using Eq(9). The minimum area, A_k is calculated by using Eq(6).

$$A_k = \frac{Q_k}{\Delta T_{LMK}}\left(\frac{1}{h_{h,k}} + \frac{1}{h_{c,k}}\right) \tag{6}$$

$$\Delta T_{LMK} \approx \left((T_{H1} - T_{C2})(T_{H2} - T_{C1})\left(\frac{(T_{H1} - T_{C2}) + (T_{H2} - T_{C1})}{2}\right)\right)^{1/3} \tag{7}$$

Where Qk is the heat transferred in the heat exchanger (kW), T_H is temperature for hot stream (°C) and T_C is temperature for cold stream (°C), $h_{h,k}$ and $h_{c,k}$ are heat transfer coefficient for hot and cold stream (kW/m^2.°C).

2.7 Step 7: Heat Exchanger Selection and Cost Calculation

Several criteria are considered during the selection of heat exchanger. For examples, the phases of hot and cold streams, pressure and temperature range of streams, and area of heat exchanger required. When there is more than one type of heat exchangers that fulfill the criteria of selection, the type of heat exchanger with the lowest capital cost is chosen. The heat exchangers that fulfill the selection criteria are shell-and-tube, double-pipe, spiral plate and spiral tubes heat exchanger. The capital cost is calculated based on Seider et al. (2010) for each heat exchanger costing equations.

2.8 Step 8: Calculation of Total Annual Cost and Payback Period

After the capital cost for each heat exchanger (Step 7) and annual utilities costs (Step 5) are calculated, the total annual cost for the HEN is calculated. The total annual cost of HEN is the summation of total annualised capital cost and annual utilities cost. In order to calculate the total annualised capital cost, the equipment life and rate of return as are needed. The total annualised capital cost, A_T can be calculated by using equation below (Blank and Tarquin, 2012):

$$A_T = P_T \times \left(i(1+i)^n/(1+i)^n - 1\right) \quad (8)$$

Where P_T is total capital cost (USD), i is rate of return (%) and n refer to equipment life (year). The payback period can then be calculated by using Eq(9).

$$\text{Payback period} = P_T/C_S \quad (9)$$

Where P_T is total capital cost (USD) and C_S is total cost saving (USD/year).

3. Industrial Case Study

Process streams involving isothermal phase change have been discussed and applied with modified STEP in the previous section. In this section, the modified STEP procedure is applied on a case study involving process streams undergoing non-isothermal phase change. Table 1 shows the stream data for this case study. Note that this case study was previously solved using conventional Composite Curves by Liporace et al. (2004). The results obtained using the modified STEP are compared with those obtained using the Composite Curves.

Table 1: Stream data for all streams (Liporace et al., 2004)

Stream	T_s (°C)	T_t (°C)	F (kg/s)	Cp (kJ/kg.°C)	FCp (kW/°C)	ΔH (kW)
H1	120	65	12.7	3.94	50	2,750
H2	80	50	122.6	2.45	300	9,000
H3	135	110	27.1	10.70	290	7,250
H4	220	95	4.2	4.72	20	2,500
H5	135	105	27.6	9.42	260	7,800
C1	65	90	59.3	2.53	150	3,750
C2	75	200	29.6	4.73	140	17,500
C3	30	210	24.9	4.02	100	18,000
C4	60	140	8.6	5.83	50	4,000

Table 2: Data extraction for shifted supply and target temperatures involving phase change

Stream		**Phase**	**F (kg/s)**	**T_s (°C)**	**T_t (°C)**	**Cp (kJ/kg.°C**	**FCp (kW/°C)**	**ΔH (kW)**	**T_s' (°C)**	**T_t' (°C)**	**H (kW/m^2.°C)**
H1	H1a	L+V	12.7	120.0	110.0	9.87	125.35	-1,253.5	110.0	100.0	8.02
	H2b	L	12.7	110.0	65.0	2.62	33.27	-1,497.3	100.0	55.0	2.16
H2	H2	L	122.6	80.0	50.0	2.45	299.96	-8,998.8	70.0	40.0	2.11
H3	H3	L+V	27.1	135.0	110.0	10.72	290.51	-7,262.8	125.0	100.0	6.23
H4	H4a	V	4.2	220.0	141.4	2.44	10.26	-806.4	210.0	131.4	2.03
	H4b	L+V	4.2	141.4	110.0	11.35	47.68	-1,497.3	131.4	100.0	7.48
	H4c	L	4.2	110.0	95.0	2.77	11.62	-174.3	100.0	85.0	1.22
H5	H5a	L+V	27.6	135.0	110.0	10.72	295.87	-7,396.8	125.0	100.0	11.95
	H5b	L	27.6	110.0	105.0	2.90	80.04	-400.2	100.0	95.0	2.09
C1	C1	L	59.3	65.0	90.0	2.53	149.91	3,747.76	75.0	100.0	2.46
C2	C2a	L	29.6	75.0	110.0	2.66	78.74	2,755.76	85.0	120.0	1.43
	C2b	L+V	29.6	110.0	141.4	11.35	336.06	10,552.4	120.0	151.4	8.61
	C2c	V	29.6	141.4	200.0	2.41	71.42	4,185.44	151.4	210.0	2.02
C3	C3a	L	24.9	30.0	110.0	2.50	62.19	4,975.02	40.0	120.0	1.21
	C3b	L+V	24.9	110.0	141.4	11.35	282.70	8,876.85	120.0	151.4	7.78
	C3c	V	24.9	141.4	210.0	2.43	60.47	4,148.34	151.4	220.0	1.81
C4	C4a	L	8.6	60.0	110.0	2.60	22.38	1,118.86	70.0	120.0	2.51
	C4b	L+V	8.6	110.0	140.0	11.20	96.29	2,888.74	120.0	150.0	14.57

Supply and target temperatures of hot and cold streams are converted into shifted temperatures by subtracting hot streams temperature with the minimum temperature difference, ΔT_{min} which is assumed as 20 °C. Both shifted temperatures for hot and cold streams are shown in Table 2. To construct hot and cold STEPs streams, the average FCp of hot and cold streams which consists sub-streams due to phase change are calculated first.

Next, the individual hot streams are plotted according to their FCp_{av}. The Pinch Point and minimum utilities are determined from the STEP by shifting each continuous cold stream horizontally until it pinch the hot stream. Note that the cold stream should be below, and on the right hand side of the hot stream. The matching is continued until all hot and cold streams are matched and pinched. The annual utility cost for this case study is shown as in Table 3.

Table 3: Total utility cost

Utility	Total Qmin (kW)	Rate (USD/kW.y)	Annual Utility Cost (USD/y)
Hot	26,334.8	120.0	3,160,176
Cold	12,373.1	10.0	123,731
		Total	3,283,907

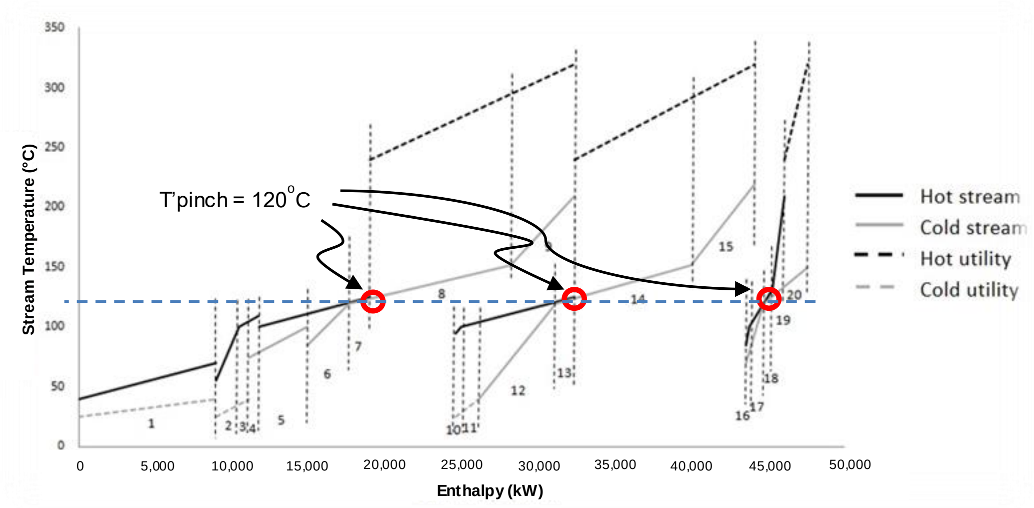

Figure 1: Area targeting using STEP

As shown in Figure 1, there are 20 segments in STEP based on minimum area targeting and selected based on the selection criteria for the heat exchangers. Since there is more than one type of heat exchanger that can be used, the selection is made based on the capital cost estimate for each heat exchanger. Shell-and-tube heat exchanger has been selected due to its compatibility and lower cost. The same procedure in heat exchanger selection is carried out for the other heat exchangers needed. Rate of return (i) for this case study is assumed as 10 % with the equipment life (n) of 6 y. The total annualised capital cost is USD 142,335/y and the total annual cost (capital and operating) is USD 3,426,241/y. The total cost saving, C_S and energy saving for both hot and cold utilities are USD 2,198,872/y and 16,914.4 kW. The payback period is 0.28 y by using the modified STEP. This is shorter than the payback period of 0.43 y obtained using Composite Curves.

4. Conclusion

A new graphical method for HENS involving phase changes has been proposed. Result from the presented case study shows that the modified STEP is an effective visualisation tool for HENS involving phase changes as it enables designers to graphically and simultaneously target the minimum utilities and design a HEN to achieve the minimum number of units. In modified STEP, all the process streams are plotted and mapped individually and hence the matching and heat transfer between hot and cold streams are clearly shown. This allows different types of heat exchangers to be selected for heat exchange between hot and cold streams. As a result, the total capital cost for heat exchangers required is decreased using modified STEP as the suitable heat exchanger with the lowest capital cost is chosen for each matching. In conclusion, the modified STEP is a useful graphical approach for HENS involving phase changes since it can easily be used even for systems involving threshold problems and multiple pinches and can provide more realistic solutions for targeting multiple utilities and the minimum network area based on individual hot and cold streams.

5. Recommendation

In order to achieve minimum utility targets, stream splitting has been considered in the modified STEP. The case study applying the modified STEP has not included loop breaking and threshold problems. Extended case studies that include loop breaking and/or threshold problem can be considered in future applications of the modified STEP approach.

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