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Utility-Heat Exchanger Grid Diagram: A Tool for Designing the Total Site Heat Exchanger Network

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The world industrial energy consumptions have gained the focus from the sustainability experts. Industrial Energy Efficiency is one of the important aspects that contributed to the energy consumptions. Process Integration using Pinch Analysis is a very well established tool for energy conservation through systematic design methodology of Heat Exchanger Network – HEN. The HEN for heat recovery within a single process is design using the Grid Diagram. The streams temperature and heat duty are the main aspect in design a HEN through Grid Diagram. The hot utility at above Pinch region is typically placed at the highest temperature, while cold utility at below Pinch is located at lowest temperature. Heat Integration is extended for covering multiple processes heat recovery via utility system, known as Total Site Heat Integration. There is a lot of research done on graphical and numerical targeting of the minimum utility requirement for a Total Site (TS) system. Some mathematical models of the TS utility system have been introduced to optimise the TS utility consumption. However, these methodologies have not discussed the heat exchanger arrangements in the TS HEN. The heat exchangers arrangement in a TS system should be able to produce steam at the high temperature, while the hot utility consumption should be placed as low temperature as possible. This design requirement is not the same as the design terminology for Grid Diagram in single process heat integration. In this paper, the Utility-HEN Grid Diagram is introduced for assisting the HEN design for a TS system to maximise the heat recovery using indirect heat transfer. This tool is able to visualise the heat transfer between processes in the TS system. The Utility-HEN Grid Diagram allows the heat exchangers to be designed according to utility temperature. The design process would be very much beneficiated by the Multiple Utility Problem Table Algorithm (MU-PTA) and the Total Site Utility Distribution (TSUD) Table. The methodology is demonstrated by an illustrative case study.

1. Introduction

Heat Integration (HI) is introduced to enhance energy efficiency in chemical processing industry. Pinch analysis is a well-established concept, which is widely used for targeting energy consumption, designing the Heat Exchanger Network (HEN) and identifying process integration opportunities (Klemeš, 2013). The HI concept has been extended from individual process level to a Total Site (TS) level, which comprises of several processes or industrial clusters (Dhole and Linnhoff, 1993). The TS HI methodologies are well developed using the graphical (Fodor et al., 2012) and numerical (Liew et al., 2012) methodology. The methodologies are proposed for targeting the minimum energy requirement of TS system. A lot of efforts are used to optimise the utility system and cogeneration system in TS context (Velasco-Garcia et al., 2011).
Grid Diagram (GD) is the most common used methodology for designing the HEN in the single processing plant integration (Linnhoff et al., 1982). There are other tools proposed for designing the HEN. Wan Alwi and Manan (2010) proposed a novel methodology for simultaneous targeting and designing HEN. Mizutani et al. (2003) performed a HEN synthesis using mathematical programming model based on trade-off between piping cost and heat transfer area. Soršak and Kravanja (2002) introduced MINLP model for HEN synthesis

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based on different heat exchanger type selection. Pejpichestakul and Siemanond (2013) perform a process retrofit ensuring cost-effective HEN using mathematical optimisation methodology. Morrison et al. (2012) proposed a mathematical model extension to design HEN for non-continuous processes.

Liew et al. (2014) proposed the TS retrofit framework. Appropriate utility placement at heat sink and heat sources are identified as an important factor for improving utility consumption in TS. It is important to ensure that the utility is placed correctly in the design stage. Individual process HEN design typically does not consider steam generations by process streams for indirect heat transfer between processes. The HEN design in TS Heat Integration is indeed important to ensure steam consumption and generation take place at the appropriate utility levels. The Utility-HEN Grid Diagram is proposed in this work for designing TS HEN, steam boilers and steam consumers according to the utility temperature. The TS energy targeting method considering water sensible heat (Liew et al., 2014) is used in this methodology in order to include the boiler feed water preheat, evaporation and superheat in the HEN design.

2. Methodology

The overall HEN synthesis methodology aided by Utility-HEN Grid Diagram is described as below:

2.1 Step 1: Extract stream data

The process stream data is extracted from the process design flow sheet, which are mass flow rate ($\dot{m}$), heat capacity (Cp), supply temperature (T_s), target temperature (T_t) and heat duty (ΔH).

2.2 Step 2: Target utility consumption

Multiple utility requirement of single process is first determined using Multiple Utility - Problem Table Algorithm (Liew et al., 2012). The TS utility consumption considering energy consumption for water sensible heat is then targeted using the modified TS- Problem Table Algorithm proposed in Liew et al. (2014). The amount of energy determined for steam preheat and superheat in the proposed methodology are identified as the heat duty for preheater and superheater. The energy flow between processes and utility system is then able to be illustrated in the modified Total Site Utility Distribution (TSUD) Table. The energy consumptions for preheater and superheater, as well as steam produced via condensate recovery, are recorded in the TSUD table. These tools aids the process of HEN synthesis for a TS together with preheater, evaporator and superheater included.

2.3 Step 3: Construct Utility-HEN Grid Diagram

The Utility-HEN Grid Diagram is an extension of the Grid diagram for HEN design in conventional Pinch Analysis. The heat exchangers are represented according to the temperature profile in the Utility-HEN Grid Diagram. This would actually eliminate the step for checking minimum temperature using temperature - enthalpy diagram for counter flow heat exchangers. The steps and heuristics are summarised as following:

(1) Draw the utilities temperature and stream lines according to its respective normal temperature. Shifted utility temperature is added for hot streams at utility below pinch temperature with minimum allowable temperature difference between utility and processes ($\Delta Tmin_{u,p}$) added to the utility temperature (Eq.1). Utility temperature at below Pinch temperature is added for cold stream by deducting $\Delta Tmin_{u,p}$ from utility temperature (Eq.2).

Hot streams at below Pinch Region:

$$\text{Shifted utility temperature} = \text{Utility temperature} + \Delta Tmin_{u,p} \quad (1)$$

Cold streams at above Pinch Region:

$$\text{Shifted utility temperature} = \text{Utility temperature} - \Delta Tmin_{u,p} \quad (2)$$

(2) Design the network together with preheater (PH), evaporator (EV) and superheater (SH) for all the processes based on Multiple Utility – Problem Table Algorithm or TSUD table. The design should be done according to temperature interval between utility temperature and Pinch temperature.

Heuristic 1: Start the network design with the interval which is immediately above and immediately below Pinch temperature.

Heuristic 2: If steam generation is required in the temperature interval, assign process-to-process heat exchangers, before steam generation equipment. For process-to-process heat exchangers, use CP rules (Eq.3) to determine stream pairs for process-to-process heat exchange, which heat capacity flow rate (CP) flowing outwards the Pinch temperature should be larger or equal to the CP flowing towards the Pinch temperature.

$$CP_{out} \geq CP_{in} \quad (3)$$

Heuristic 3: Cross utility process-to-process heat exchange is allowed for utilising heat sources from higher temperature to lower temperature interval. Cross-process Pinch heat transfer is strictly not permissible.

Heuristic 4: If steam generation is required in the temperature interval, preheater should be placed nearest to the low boundary in respective temperature interval, while superheater should be allocated close to high boundary.

Heuristic 5: Stream splitting is considered when the energy consumption higher than the targeted energy requirement in Step 2.

Heuristic 6: Use heat loop or heat path terminology (Klemeš, 2013) to minimise the number of heat exchangers use in the network design.

3. Case Study

An illustrative case study is used to demonstrate the methodology proposed in this work. This case study consist of two processes with four utility types serving the plant, which are High Pressure Steam (HPS – 270 °C), Low Pressure Steam (LPS – 133.5 °C) and Cooling Water (CW – 25 °C). Table 1 shows the streams data together with minimum allowable temperature difference between processes ($\Delta T_{min,pp}$) and between process and utility ($\Delta T_{min,up}$).

Table 1: Stream data for Illustrative Case Study

Stream	T_s (°C)	T_t (°C)	ΔH (MW)	$\dot{m}C_P$ (kW/°C)	Stream	T_s (°C)	T_t (°C)	ΔH (MW)	$\dot{m}C_P$ (kW/°C)
Process A ($\Delta T_{min,pp}$ = 20 °C; $\Delta T_{min,up}$ = 10 °C)					Process B ($\Delta T_{min,pp}$ = $\Delta T_{min,up}$ = 10 °C)				
H1A	200	100	20.0	200	H1B	200	50	04.50	30
H2A	150	60	36.0	400	H2B	240	100	02.10	15
C1A	50	120	49.0	700	H3B	200	119	18.63	230
C2A	50	220	25.5	150	C1B	30	200	06.80	40
					C2B	50	250	04.00	20

The data is analysed using the modified TS-PTA methodology (Liew et al., 2014) for determining the utility requirement at different level, the amount of energy consumed by BFW preheat, as well as steam superheat. The amount of energy recovered from condensate is also targeted in this step. A total of 10,778 kW of energy from boiler is consumed at the LPS (3,778 kW) and HPS (7,000 kW) heaters, while total cooling requirement of the TS is 7,283 kW. Based on the targeting result using modified TS - Problem Table Algorithm, energy consumption on water sensible heat, a total of 2,147 kW of energy is consumed for producing 4.623 kg/s of MPS. In order to produce this amount of MPS, 2,044 kW of heat source are used to preheat the boiler feed water and 103 kW of energy is consumed for superheating saturated steam. HPS condensate is flashed to LPS, which recovers 2,721 kW of LPS for process usage. The amount of energy consumptions are recorded in the Total Site Utility Distribution - TSUD table (Table 2). The energy flows between processes and utilities are clearly illustrated by using this tool.

Table 2: Modified Total Site Utility Distribution (TSUD) table

	Heat Sources (kW)				Heat Sinks (kW)				
	Process		Utility		Process		Utility		
	A	B	Recovery	Heaters	A	B	Preheaters	Superheaters	Coolers
HPS	0	0	-	7,000	6,000	1,000	-	-	-
LPS	0	12,148	2,721	3,778	16,500	0	2,044	103	-
CW	4,000	3,283	-	-	0	0	-	-	7,283

The streams, Pinch and utility temperature are first plotted in the Utility-HEN Grid Diagram as Figure 1. For Process A, the $\Delta T_{min,up}$ is added to utility temperature at below Pinch region for hot streams, which the effective CW temperature for hot streams is shifted to 25 °C. In above Pinch region, the $\Delta T_{min,up}$ is deducted from the utility temperature for cold stream. For example, LPS temperature shifted to 123.5 °C for cold streams in Process A. In Process B, LPS is below Pinch temperature. The LPS temperature is added with $\Delta T_{min,up}$ to 143.5 °C. The temperature intervals for HEN design are identified in Figure 1.

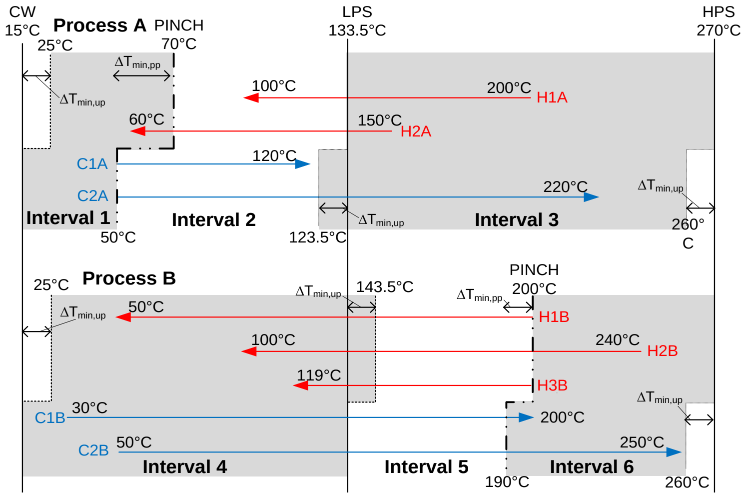

Figure 1: Utility-HEN Grid Diagram

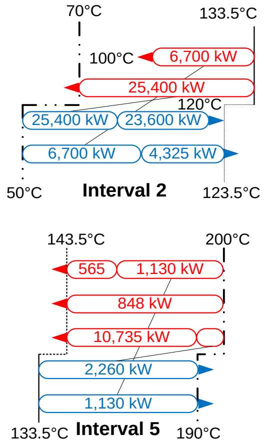

Figure 2: Example of preliminary HEN design for Interval 2 & 5

According to “Heuristic 1”, the HEN design should start from the Pinch temperature, which means Interval 2 should be design before Interval 3. The HEN for Interval 5 should be designed before Interval 4. HEN design for Interval 2 and 5 are used to demonstrate “Heuristics 2 - 4”.

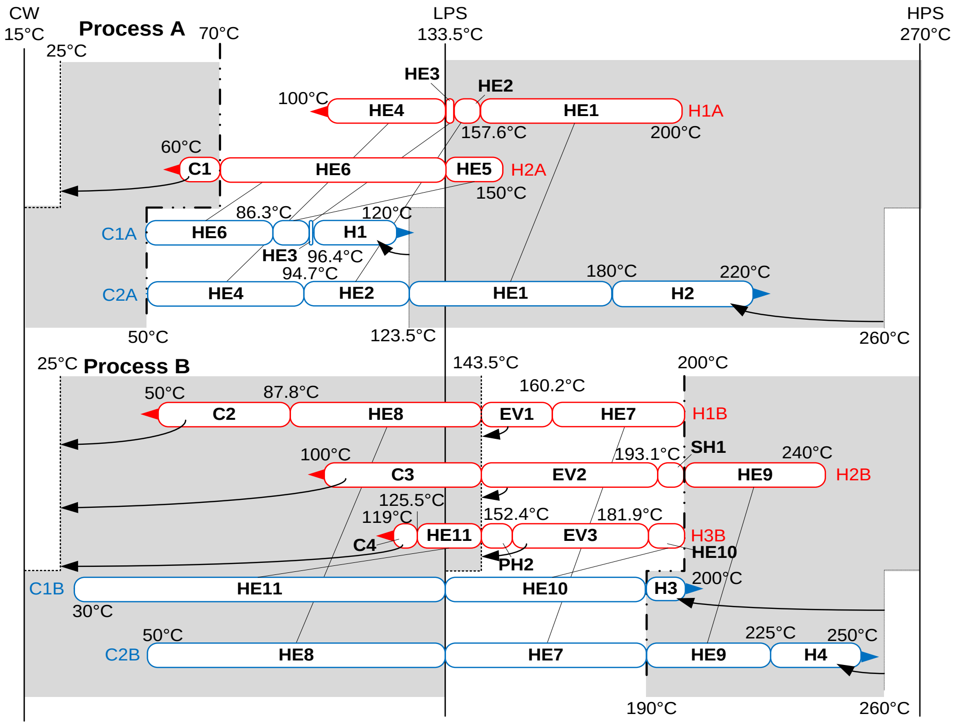

Figure 3: HEN design with Utility-HEN Grid Diagram

In the preliminary HEN design for Interval 2, process-to-process heat exchangers are designed at the first place (Heuristic 2). There are remaining 29,725 kW (25,400 + 4,325 kW) of unsatisfied cooling demands in this temperature interval. These demands need to be heated by process heat sources or steam at LPS level. However, the Modified TSUD table (Table 2) shows Process A consists 16,500 kW of process heat sinks, which means that there is excess cooling demand in this design. Cross-utility heat transfer without crossing process Pinch is allowed in TS HEN design (Heuristic 3). The excess cooling demand is allowed to be heated

by process heat sources at Interval 3. The cooling demands of C1A and C2A are partially heated by excess heat sources at Interval 3, which are shown as HE2 and HE3 in Figure 3.
Similar to Interval 2, Interval 5 should be designed before Interval 4 (Heuristic 1). According to “Heuristic 2”, process-to-process heat exchange opportunities are first identified for the preliminary HEN design for Interval 5 as shown in Figure 2. After considering heat recovery within temperature interval is considered, there are 12,148 kW of heat sources in excess for steam generation (Heuristic 4) or process-to-process heat exchange (Heuristic 3). This amount of excess energy tally with Table 2, in which 2,044 kW, 10,001 kW and 103 kW of energy is consumed by preheater, evaporator and superheater for generating LPS. “Heuristic 4” is used for assigning steam generation equipment in Interval 5. Superheater should be allocated at the higher boundary of the temperature interval. The 103 kW superheater (SH1) is placed at stream H2B, due to the high temperature heat sources in another two streams are consumed for heat recovery within process. A preheater is assigned at the stream H3B due to energy content remained in other streams are insufficient to satisfy the requirement. Lastly, evaporators are allocated to utilise the heat sources in all the streams for generating LPS. The new utility system and HEN is designed according to temperature intervals and shown in Figure 3.
Split streams (Heuristic 5) are not required to be performed in this case study, because the network design achieved the maximum heat recovery as suggested in the targeting step. The HEN design in Figure 2 can be evolved by heat loop and path (Heuristic 6). HE1, HE2 and HE4 are exchanging energy between H1A and C2A. These heat exchangers could be combined for reducing the capital cost involved, if the heat load of HE3 moved to lowest temperature. HE5 and HE6 could also be combined for reducing the number of heat exchangers. The final HEN design is shown in Figure 4, while the equipment heat duties are listed in Table 4.

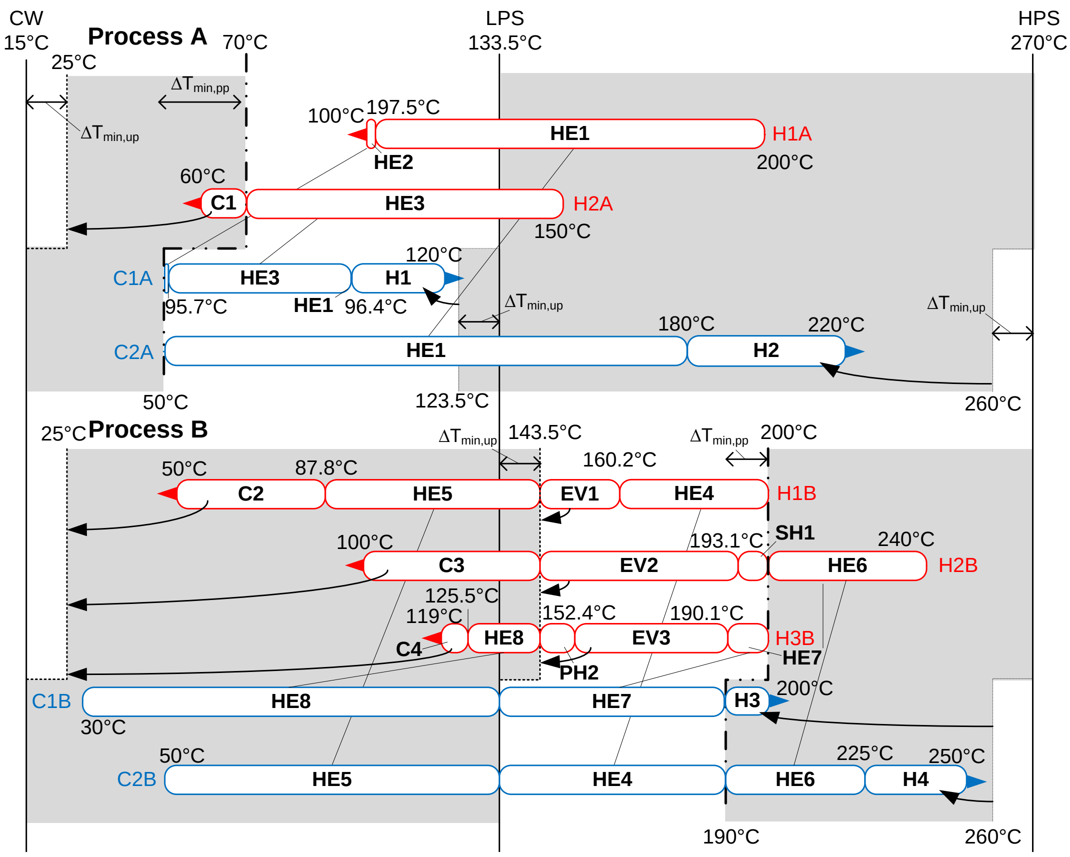

Figure 4: Final HEN design with Utility-HEN Grid Diagram after evolution with heat loops

4. Conclusion

The Utility-HEN Grid Diagram is proposed in this work to design a TS HEN. The proposed methodology is an extension for Grid Diagram in conventional Pinch Analysis. The equipment’s’ temperature profile are illustrated in the Utility-HEN Grid Diagram. This feature replaced the temperature profile checking using enthalpy-temperature profile. Heuristics for Grid Diagram are enhanced for the HEN design considering steam

Table 4: Equipment heat duties for the HEN design in Utility-HEN Grid Diagram

Equipment	Duty (kW)	Equipment	Duty (kW)	Equipment	Duty (kW)	Equipment	Duty (kW)
HE1	19,500	HE7	2,260	SH1	103	H1	16,500
HE2	500	HE8	4,140	C1	4,000	H2	6,000
HE3	32,000	EV1	565	C2	1,134	H3	400
HE4	1,130	EV2	744	C3	652.5	H4	600
HE5	1,670	EV3	8,691	C4	1,495		
HE6	600	PH1	2,044				

generation using process hot streams. The proposed methodology is able to design HEN with targeted energy requirement using Modified TS - Problem Table Algorithm and illustration on Modified TS Utility Distribution table. The proposed methodology is ensuring that the TS utility consumption take place at correct utility level. In TS HEN design, high temperature heat sources are properly utilised and energy consumption consequently reduced in TS context. The Utility-HEN Grid Diagram is drawn according to heat exchanger’s inlet/outlet stream temperature. This reduced the effort to perform temperature check using temperature - enthalpy diagram.

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