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A New Technique for Heat Exchanger Network Retrofit Using Individual Stream Heat Cascade Analysis

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Rising energy demand and concern for environmental emissions have encouraged researchers to explore variety of methods for retrofit of heat exchanger networks (HEN). Current graphical and insight-based HEN retrofit methods have some common limitations. Most of the techniques may involve tedious graphical constructions, iterative calculations, or use of multiple diagrams to accomplish HEN retrofit. This paper introduces a new HEN retrofit method called the Individual Stream Heat Cascade Analysis (ISHCA) Technique. Within a single diagram called the Heat Cascade Table (HCT), ISCHA simultaneously show individual hot and cold streams heat allocation, identify the Pinch point and determine the minimum utility requirements to guide HEN retrofit that observes the Pinch design rules. Application of ISCHA technique on an illustrative case study shows reductions of 72 % hot utility and 66 % cold utility from the existing HEN. ISHCA combines numerical precision and efficiency with visualization insights to yield results that are comparable to other retrofit methods.

1. Introduction

Pinch Analysis (PA) has been a well-established method for heat exchanger network (HEN) synthesis since the early 1970s. The method is used as a tool to lay out the supply and demand to achieve a minimum external energy demand in HEN (Gaikwad and Ghosh, 2020). Since then, Pinch Analysis concept has been extended for the development of numerous techniques for conservation of resources beyond energy. There are various examples of PA applications other than for heat exchanger network. These include network of mass exchanger, network of water utilization and network of energy-mix for electricity generation (Su et al., 2020). Composite Curves (CC) and Problem Table Algorithm (PTA) are the two well-known methods known for HEN synthesis that use the concept of PA to maximize heat recovery and minimize the demand for external utilities. Walmsley et al. (2017) introduced a new modified Energy Transfer Diagram (ETD). This method identifies segments of the ETD that illustrate heat surpluses and deficit in the HEN and then projects it inside the ETD. The information was then used to determine the HEN retrofit alternatives and heat energy recovery. Lai et al. (2018) then extended the use of modified ETD by combining it with Stream Temperature vs Enthalpy Plot (STEP) diagram. The modified ETD was used to monitor the development of HEN retrofit that was carried out by using STEP diagram. Isafiade and Short (2020) used STEP method to identify potential streams for HEN retrofit and design the HEN retrofit using a mixed integer non-linear (MINLP) model. Alhajri et al. (2021) applied a T_{hot} versus T_{cold} graph on an existing HEN in a refinery in Kuwait to improve energy saving and reduce annual operating cost. Wang et al. (2021) developed a new graphical method to search for the minimum total annualized cost (TAC) of HEN retrofit. The method was based on constrained particle swarm optimization (PSO) algorithm where several type of utility prices are considered and the algorithm was used to optimize the heat exchanger temperatures to achieve minimum TAC. HEN retrofit using STEP is a new graphical technique that enables a HEN retrofit problem to be solved just by using an individual stream temperature vs enthalpy diagram (Lai et al., 2017). The key advantage of STEP is its ability to explicitly show the mapping of heat sources to demands since it is built based on individual streams as opposed to CC. Due to the typically high level of customisation, experience and expert knowledge required in solving a retrofit problem, most of the developed retrofit methods,

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including STEP, have been based on graphical, insight-based techniques. Graphical tools typically provide useful visualization insights while numerical techniques offer the advantage of calculation precision and efficiency (Abbood et al., 2012). Current graphical and insight-based HEN retrofit methods typically involve tedious graphical constructions, iterative calculations or require multiple diagrams. A new HEN retrofit method known as the Individual Stream Heat Cascade Analysis (ISHCA) technique is proposed in this paper. ISCHA enables designers to simultaneously map individual hot and cold streams, identify the Pinch point and determine the minimum utility requirements to guide HEN retrofit using a single diagram called the Heat Cascade Table (HCT). ISHCA combines numerical precision and efficiency with visualization insights to yield results that are comparable to other retrofit methods.

2. A new technique for heat exchanger network retrofit using Individual Stream Heat Cascade Analysis

ISHCA HEN retrofit method comprises of the diagnosis and retrofit stages The diagnosis stage involves representation of HEN into a Heat Cascade Table (HCT) and identification of potential process streams to undergo retrofit. HEN retrofit is then performed on selected potential streams.

Figure 1 is a case study from Klemeš et al. (2014) that is applied to illustrate the ISCHA method. There are two hot streams (stream H1 and H2) and two cold streams (stream C1 and C2) for this case study. The minimum approach temperature (ΔT_{min}) is set at 10 °C. The shifted Pinch temperature is at 145 °C. The hot utility requirement, Q_h from HU1 is 2,700 kW and the cold utility requirement, Q_c from CU1 and CU2 is 2,950 kW. There are two existing heat exchangers, E1 with a heat load of 800 kW and E2, 2,400 kW. The heat capacity flowrate (FCp), for stream H1 is 15 kW/°C, H2 is 25 kW/°C, C1 is 20 kW/°C and C2 is 30 kW/°C.

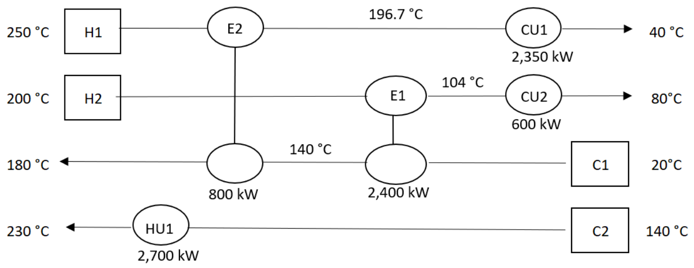

Figure 1: The stream data of existing HEN a) grid diagram of the HEN b) Stream data for the case study

2.1 Diagnosis stage

The diagnosis stage refers to the construction of HCT, representing the existing HEN on HCT, and identification of potential streams for retrofit.

Step 1: Construction of HCT. Arrange the shifted temperatures in Column 1 and temperature interval difference, ΔT in Column 2 in descending order (see Table 1 and 2).

Once the HCT is constructed, the existing HEN is represented on the HCT as described next in Steps 2 to 4 of the ISHCA technique.

Step 2: Reconstruct stream heat allocation for the existing HEN by placing hot and cold streams sequentially in the appropriate Stream Heat Allocation Cluster (SHAC). Start by placing the hot stream with the largest FCp first within a SHAC, according to the stream's temperature interval. Process-to-process stream heat exchange is indicated by associating the stream name to the existing heat exchanger or utility heater/cooler (e.g.: stream H2-E1 refers to hot stream H2 that is connected to heat exchanger E1).

As shown in Table 1, the hot stream H2 in column 3 having the largest FCp and running from interval temperatures of 195-75 °C is first placed within Hot SHAC 1. So, H2-E1 refers to stream H2 allocating heat to cold streams via heat exchanger E1 in the 195-75 °C temperature interval. Next, the Hot SHAC 1 is completed by identifying the set of cold streams receiving H2 heat. H2-CU2 in the 145-75 °C interval refers to the temperature interval where H2 is connected to cooler CU2.

Step 3: Place the cold stream receiving heat from the hot stream through a heat exchanger or utility. For example, H2 in temperature interval 195-75 °C is connected to stream C1 in temperature interval of 145-25 °C through heat exchanger E1. So, in SHAC 1 of Table 1, C1-E1 shown in column 6 represents the cold stream from interval 145-25 °C that receives heat from hot stream H2 via heat exchanger E1. Columns 4 and 7 show the enthalpy change, ΔH for each heat.

Table 1: Heat cascade table (HCT) for the existing heat exchanger network (HEN) in SHAC1 and SHAC 2

1	2	3	4	5	6	7	8	9	10	11	12
		SHAC 1					SHAC 2				
T' (°C)	Δ T (°C)	Hot	Hot SHAC ΔH (kW)	Stream Match	Cold	Cold SHAC ΔH (kW)	Hot	Hot SHAC ΔH (kW)	Stream Match	Cold	Cold SHAC ΔH (kW)
245											
	10						H1-E2	150	150		
235											
	40						H1-E2	600	600		
195											
	10	H2-E1	250	250			H1-E2 H1-CU1	150	50 100		
185											
	40	H2-E1	1,000	1,000			H1-CU1	600	600	C1-E2	800
145											
	70	H2-E1 H2-CU2	1,750	150	C1-E1	1,400	H1-CU1	1,050	1,050		
75				800							
	40				C1-E1	800	H1-CU1	600	600	CU1	2,350
35				200							
	10				C1-E1	200					
25				600							
					CU2	600					

Table 2: Heat cascade table (HCT) for the existing heat exchanger network (HEN) in SHAC 3

1	2	13	14	15	16	17
T' (°C)	Δ T (°C)	SHAC 3 Hot	Hot SHAC ΔH (kW)	Stream Match	Cold	Cold SHAC ΔH (kW)
245						
	10					
235						
	40	HU1	2,700	1,200	C2-HU1	1,200
195						
	10			300	C2-HU1	300
185						
	40			1,200	C2-HU1	1,200
145						
	70					
75						
	40					
35						
	10					
25						

The direction and amount of heat cascade is shown by the black arrow connecting the hot and cold stream segments via a heat exchanger. Note that, in line with the second law of thermodynamics, heat can only be cascaded to a lower temperature interval or within the same shifted temperature interval (with built in ΔT_{min}). Referring to columns 3-7 of Table 1, it can be seen that H2-E1 at temperature interval of 195-185 °C allocates 250 kW of heat to C1-E1 at temperature interval of 145-75 °C. The number above the arrow (e.g., 250 kW) represents the heat load cascaded or exchanged from the hot stream segment to the cold stream segment, within the streams' temperature intervals.

Step 4: Repeat steps 2 and 3 for the remaining streams, taking care to place new streams within a new SHAC (see Table 1 and 2).

Step 5: Clearly indicate the temperature interval where the Pinch temperature exists. Pinch temperature can be obtained using CC, PTA, STEP (Wan Alwi and Manan, 2010) or other Pinch design tools. Tables 1 and 2 show the shifted Pinch temperature at 145 °C for this case study.

Step 6: From the completed HCT, potential streams are determined and the targeted streams are selected. Potential streams are the streams with high energy demand, or that lead to energy inefficiency or losses. For example, streams that violate the Pinch rules and streams that require significant utility from outside sources. Users may include streams that they desire to explore for additional heat recovery as potential streams, even if the streams do not violate Pinch rules. For this case study, streams match of E1 and E2 as well as cooler CU1 cross the Pinch temperature and violate Pinch rule. Stream C2-HU1 is also included since its heat demand is fulfilled by a heater and has a potential to be match with other hot streams.

In order to have a significant utility cost-savings reduction, it is ideal to include all streams especially where there is a not-so complex network (e.g.: a retrofit project involving around ten streams). Most of the times not all potential streams are selected for retrofit due to high retrofit cost. The chosen potential streams are called targeted streams (Lai et al., 2017). For a simple case study with few streams such as this one, all potential streams are included as targeted streams to undergo the retrofit. The heat cascade matches involve all streams as well as cooler CU1, CU2, and heater HU1. Stream H1, H2, C1 and C2 are selected as targeted streams to undergo retrofit.

2.2 Retrofit stage

The proposed retrofit steps are described below;

Step 1: Remove cross Pinch matches and utilities. To do this, first remove all the targeted streams while maintaining the name of each temperature. Ensure that the streams are arranged according to their temperature interval. Heat load for utilities is deleted as well since this value may change. The name of all streams matches and utilities are maintained as before.

Step 2: Retrofit the network by allocating heat loads in adherence with the Pinch rules stated in Kemp and Lim (2020) to obtain or approach the minimum energy targets. Apply the Pinch Design rules and heuristics below to assist the process of cold and hot stream matching. Use the Pinch Design rules and a set of heuristics to assist the process of hot and cold and hot streams. The set of the heuristics are; 1) Match a high temperature hot and cold stream (Umeda et al., 1978), 2) Match a hot stream with a cold stream with closer FCp (Sama et al., 1989), 3) Match a hot stream with a cold stream with a closer heating/cooling demand, and 4) Serial heat exchanger arrangement is preferable as against to a parallel arrangement to minimize complexity.

Table 3 shows the HCT of the retrofitted HEN. The explanation of the method based on the case study is as follows. After the selected heat cascade arrows have been removed, stream matching can be performed by focusing on the targeted streams, which are the streams with no heat cascade arrows. Stream matching is performed for above and below Pinch regions separately, starting from the Pinch temperature and move outwards. For above the Pinch, all streams touch the Pinch temperature at 145 °C. It is suggested to reuse existing matches before matching new stream pair to reduce the piping cost. Hot and cold streams in the same SHAC are existing matches, for example hot stream H1-E2 and cold stream C1-E2 in SHAC 2. The FCp of hot stream H1 (15 kW/°C) is smaller than the FCp of cold stream C1 (20 kW/°C). By observing the FCp rule and heuristic 1, the heating requirement of 800 kW at cold stream C1-E2 is fulfilled by receiving heat from hot stream H1-CU1 and H1-E2 (see SHAC 2 in Table 3). There is 700 kW left at hot stream H1.

At interval 195-145 °C, there are only hot stream H2-E1 and cold stream C2-HU1 left (see Table 1). By observing the FCp rule, the two streams can be matched together. The heat load of 1,250 kW at hot stream H2-E1 is transferred to cold stream C2-HU1 (see SHAC 1 in Table 3). With that, there is 1,450 kW left at cold stream C2. The remaining 700 kW at hot stream H1 has higher temperature than the remaining cold stream C2 (see SHAC 2 in Table 1). The heat can be transferred from hot stream H1-E2 to cold stream C2-HU1. The remaining 750 kW at cold stream C2-HU1 is heated using hot utility HU1.

For the region below the Pinch (see SHAC 1 in Table 1), there is a 1,750 kW heat load from stream H2-E1 and H2-CU2 and a 2,400 kW heat load from stream C1-E1. There is not enough heat from hot stream H2 to satisfy the heat deficit of the stream C1. The heat load from C1-E1 in the interval 75-25 °C in SHAC 1 is moved to SHAC 2 to satisfy the heat deficit of the stream and cool down stream H1-CU1.

Table 3: Retrofitted configuration of HEN

1	2	3	4	5	6	7	8	9	10	11	12
		SHAC 1					SHAC 2				
T' (°C)	Δ T (°C)	Hot	Hot SHAC ΔH (kW)	Stream Match	Cold	Cold SHAC ΔH (kW)	Hot	Hot SHAC ΔH (kW)	Stream Match	Cold	Cold SHAC ΔH (kW)
							HU1	750	750		
245											
	10						H1-E2	150	150		
235											
	40						H1-E2	600	300	C2-HU1	1,200
195											
	10	H2-E1	250	50 200	[C2-HU1]'	50	H1-E2	150	250 150 50	[C2-HU1]"	250
185											
	40	H2-E1	1,000	1,000	C2-HU1	1,200	H1-CU1	600	600	C1-E2	800
145											
	70	H2-E1, H2-CU2	1,750	1,150 600	[C1-E1]'	1,150	H1-CU1	1,050	250 800	[C1-E1]"	250
75											
	40				CU2	600	H1-CU1	600	200 400	C1-E1	800
35											
	10									C1-E1	200
25											
										CU1	400

To minimize network changes that can directly affect the cost, heat load at cold utility exchanger CU2 is maintained. Heat load C1-E1 in the interval 145-75 °C is divided into two parts; [C1-E1]' and [C1-E1]" (see Table 3). Heat load of [C1-E1]' is determined by observing the remaining heat load of hot stream H2 after deducting the 600 kW at cold utility exchanger CU2. [C1-E1]' is matched with H2-E1, H2-CU2 in SHAC 1. The remaining heat load, [C1-E1]" and all heat load of C1-E1 in interval 75-25 °C are moved to SHAC 2 to match with stream H1-CU1. The remaining heat surplus at H1-CU1 is matched with CU1 (see Table 3). Figure 2 shows a grid diagram of the retrofitted network. The retrofit design consists of five units of heat exchanger and three units of utility exchanger. There are three additional units and the utilities requirement managed to be reduced. The overall results of retrofit and results comparison with existing retrofit method are shown in Table 4.

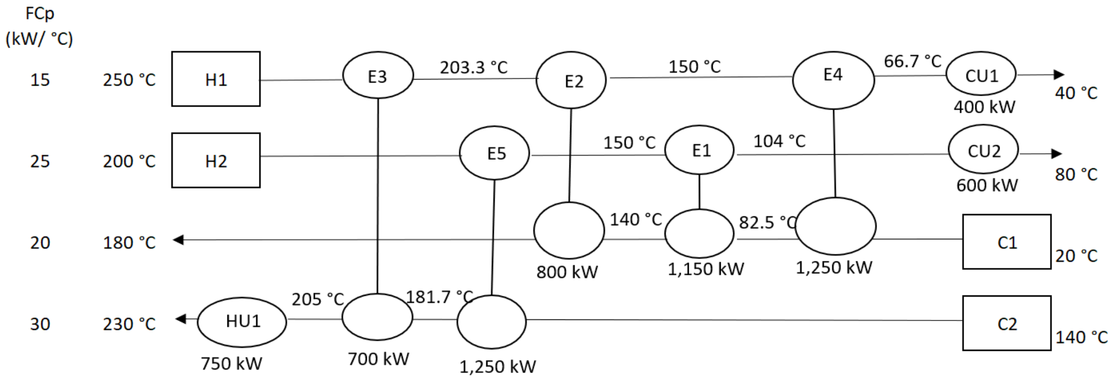

Figure 2: Grid diagram of the retrofitted network

Table 4: Results comparison with the existing network

Method	Number of units	Cold utility (kW)	Hot utility (kW)	Percentage reduced for cooling utility	Percentage reduced for heating utility
Existing network	5	2,950	2,700	-	-
ISHCA technique	8	1,000	750	66.10 %	72.22 %

3. Conclusions

A novel Pinch-based numerical retrofit method has been developed in this work to reduce utility consumption for a given HEN design. Compared to the state-of-the-art method such as CC, PTA or ETD, the newly developed method utilizes ISHCA as a tool based on individual stream concepts and allows the diagnosis and retrofit of HEN using a single diagram. Unlike STEP, HCT that is used in this method depicts surplus and deficit streams and the table is structured according to a stream interval temperature range which can be an effective tool for rapidly assessing feasible HEN retrofit possibilities. The application of the method also provides the opportunity to reduce a lengthy procedure whereby, temperature feasibility checking step using grid diagram is avoided altogether. The tabulated approach using shifted temperature and heat duty cascading allows the method to be systematically formulated and programmed in Microsoft Excel as a single retrofit procedure without the need for a grid diagram. The result shows reductions of 72 % hot utility and 66 % cold utility from the existing HEN. ISCHA combines the advantages of providing visualization insights as well as numerical precision and efficiency to yield results that are comparable to other retrofit methods.

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