Heat Exchanger Network Retrofit Considering Physical Distance, Pressure Drop and Available Equipment Space

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Heat integration has played an important role in maximising heat recovery, improving energy efficiency and reducing environmental emissions of industrial processes. However, practical aspects of heat integration such as physical distances between pipelines and space constraints must be considered especially during retrofit of heat exchanger networks (HEN). During HEN retrofit, process streams are matched based on their thermodynamic profiles to achieve energy targets. The physical distances between process streams and the space available for heat integration are usually not considered during HEN retrofit even though these issues could offset the cost savings from heat recovery. Matching of process streams across long distances may impose extra piping and pumping costs in order to overcome pressure drop. Pumping cost is also affected by elevation apart from pipeline distance. This work proposes a new graphical tool for visualising the location of process streams as well as the available space within an existing process plant, based on a proposed graphical coordinate representation. With the aid of this graphical tool, process streams can be matched not only based on their thermodynamic profiles, but also by considering the nearest physical distance and elevation of process streams. Designers can also identify the physical locations of additional equipment such as heat exchangers and pumps using the coordinate representation based on a proposed set of heuristics for equipment placement. Pumping and piping costs are included in the capital-energy trade-off analysis. Results of the study show that the coordinate representation of the existing plant can help generate a more practical HEN retrofit design for actual implementation.

1. Introduction

Pinch Analysis is an established tool for industrial resource and heat recovery for both grassroots and retrofit designs of processes. HEN retrofit poses greater challenges than grassroots HEN design due to need to preserve the existing process network structure and conditions during the course of plant retrofit to recover heat. There are various Pinch-based HEN retrofit techniques that are continuously developed by virtue of the importance and benefits brought by the technology to the industry. For instances, the Retrofit Thermodynamic Diagram (RTD) (Lakshmanan and Bañares-Alcántara, 1996), Shifted Retrofit Thermodynamic Diagram (SRTD) (Yong et al., 2014) and the Shifted Retrofit Thermodynamic Grid Diagram (SRTGD) (Yong et al., 2015) are improved versions of the conventional Grid Diagram, while the Advanced Composite Curves (ACC) (Nordman and Berntsson, 2009) and Individual Stream Temperature versus Enthalpy Curve (STEP) (Lai et al., 2018) are also inspired by the conventional Composite Curves (CC). Other graphical tools such as the process hot streams temperature versus process cold streams temperature graph (Gadalla, 2015) and the Temperature Driving Force (TDF) curve (Kamel et al., 2017) pay more attention to the streams' temperature profile. These graphical tools are used to diagnose and solve retrofit problems based on streams' thermodynamic profiles. Despite the ability to visualise stream profiles of the existing HEN, almost all of the insight-based methods neglect the practical considerations associated with physical distance, pressure drop and available space thereby leading to unrealistic retrofit designs (Marton et al., 2016).

Pressure drop constraint has been the main concern in many of the mathematical programming HEN retrofit approaches. Heat exchanger pressure drop gets the most attention amongst all other retrofit constraints. Polley

et al. (1990) identified the relationship between pressure drop, film heat transfer coefficients and heat exchanger area. Soltani and Shafiei (2011) considered pressure drop in HEN retrofit to produce more realistic result by proposing a mathematical optimisation method which coupled genetic algorithm (GA) with linear programming (LP) and integer linear programming (ILP) methods. On the other hand, distance pressure drop is highlighted in total site heat integration (TSHI). Chew et al. (2013) listed pressure drop as one of the issues affecting the practicability of TSHI. Liew et al. (2014) included pressure drop and heat loss in total site targeting methodology. Wang et al. (2014) studied on the trade-off between energy and distance related costs for different piping connection patterns across plants. Chew et al. (2015) also included distance pressure drop in total site heat integration.

Plant layout is a major constraint that hinders a HEN from achieving maximum heat recovery. Matching process streams of large physical distance imposes large piping and pumping costs. Serna-Conzález et al. (2010) included pumping cost into the total cost targeting for HEN design problem. Pouransari and Maréchal (2014) generated HEN by considering plant layout and piping cost in the calculation of investment cost, together with the heat exchanger area. Rathjens and Fieg (2018) employed the Mixed Integer Non-Linear Programming model to apply unique cost functions for each possible match. The model can consider piping and pumping costs, types of heat exchangers, as well as some additional cost factors for each individual stream.

Until now, insight-based HEN retrofit method that considers plant layout-based factors, such as physical distance, pressure drop and available space for additional heat exchanger has yet to be developed. This work proposes a coordinate representation of an existing HEN to identify available space for additional heat exchanger placement by considering physical distance and elevation.

2. Coordinate representation for existing HEN

Plant layout parameters influencing HEN design include physical distance, elevation and available space. In this work, a three-dimensional coordinate representation is proposed to visualise the aforementioned factors in retrofit. The location of the starting points and end points of the process streams can be marked on the coordinates, hence the physical distance between the process streams can be easily identified by observing the graphical representation. Hot process streams are represented in red while the cold process streams are represented in blue. The occupied space in the plant can also be indicated in the coordinates so that the available space can be considered in the retrofit design. Besides, the coordinate representation also visualizes the elevation of the process streams. By having visualization of the physical distance, available space and elevation, designers can make decision based on the heuristics proposed in this work to result in retrofit design which requires lower piping and pumping costs.

Coordinates are added to an existing HEN of the illustrative case study from Klemeš et al. (2014). A 10 °C minimum temperature approach (ΔT_{min}) is used. It is assumed that the HEN involves two plant buildings with a pipe rack between them. The existing HEN (as shown in Figure 1) is represented in the three-dimensional coordinates (as shown in Figure 2). The ratio of the coordinates with the real dimension is 1:20 meter. The process streams flow in the direction of the arrows. For this case, only one hot utility (HU) and one cold utility (CU) is applied. The utility header is located at the end of the pipe rack. The utility streams are indicated by dashed lines.
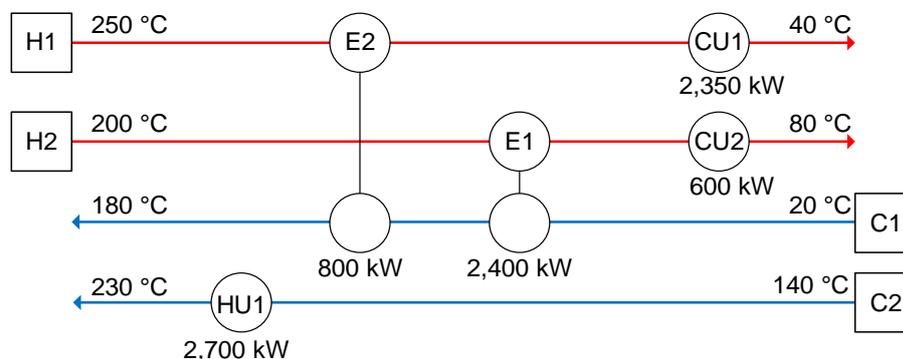

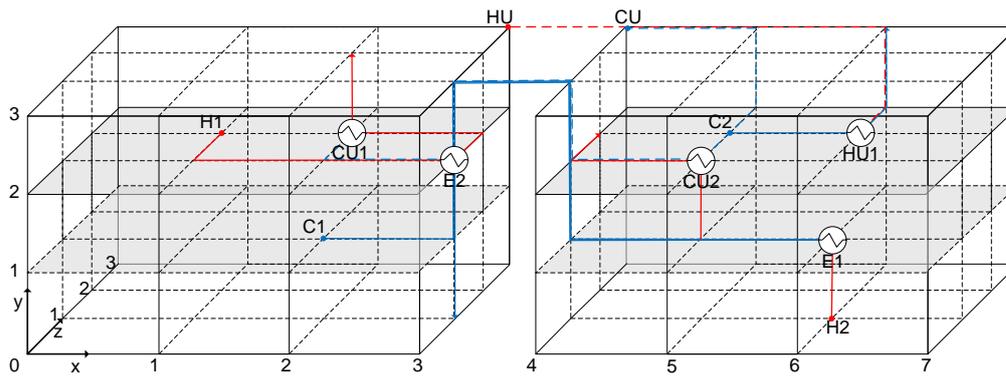*Figure 1: Grid Diagram of existing HEN (Klemeš et al., 2014)*

Figure 2: Coordinate representation of existing HEN

3. Heuristics for stream matching and heat exchanger placement

There are a few types of pressure drop in the HEN. For a typical process stream flowing in a HEN, the pressure drops encountered include the frictional pressure drop caused by the friction between the moving fluid and pipeline (ΔP_f), pressure drop across the control valve (ΔP_{CV}), pressure drop across the heat exchanger (ΔP_{HE}), and the elevation pressure drop (ΔP_E) (Chew et al., 2015). This work focusses on ΔP_f and ΔP_E which are affected by the plant layout. ΔP_{CV} and ΔP_{HE} are related to the design of the control valve and heat exchanger, usually provided by the manufacturer of the equipment. A few heuristics are proposed in this work to consider ΔP_f and ΔP_E in the retrofit design.

Heuristic 1: Match hot and cold streams of shorter distance.

When there are multiple streams available for matching, choose the process stream with the closest distance despite the elevation that the process stream has to go through. Matching process streams of shorter distance can reduce the piping cost needed, as well as the distance pressure drop experienced by the process stream and hence the pumping cost needed to overcome the pressure drop. The elevation does not affect much as the starting and end points of the process stream remain the same. For example (see Figure 2), the starting point of hot stream H1 is at (1,2,2) and the end point is at (2,3,2). During retrofit, the process stream can flow through multiple changes of elevation but the starting and end points still remain unchanged. Only the net change in fluid elevation between the starting and end points of process stream needs to be considered in order to calculate the elevation pressure drop.

After deciding the heat exchanger match, designers can utilize the coordinate representation for heat exchanger placement. For every stream pair, the heat exchanger can be placed near to either of the streams while additional piping will be required at the other stream in order to move the stream towards the heat exchanger. The heuristics proposed in this work can guide the designers to place the additional heat exchangers that will result in smaller pumping power or pipe size. Note that the application of these heuristics still depends on the space available at the plant site.

Heuristic 2: Place heat exchanger near to stream with high volumetric flowrate

Given a pair of hot and cold process streams with high and low volumetric flowrate, place the heat exchanger near to process stream with higher volumetric flowrate. The piping and pumping costs will be lower as additional pipe is added for the process stream of lower volumetric flowrate.

Heuristic 3: Place heat exchanger near to stream with high viscosity

Given a pair of hot and cold process streams with large viscosity difference, place the heat exchanger near to the process stream with higher viscosity. Lower pumping power will be required to move the lower viscosity process stream.

Heuristic 4: Place heat exchanger near to stream with higher acceptable pumping head limit

Given a pair of hot and cold process streams with both of them having positive existing pressure drop (i.e. pressure loss), place the heat exchanger near to the process stream with higher acceptable pumping head limit. Additional pump unit can be avoided if the retrofit pressure drop can be overcome by the existing pump along the process stream.

Heuristic 5: Place heat exchanger near to stream with positive existing pressure drop

Given a pair of hot and cold process streams, one having positive existing pressure drop and another with negative pressure drop (i.e. pressure gained), place the heat exchanger near to the process stream with positive existing pressure drop. The negative pressure drop which is originally meant to be released can be used to

move the process stream towards the heat exchanger. Usually, process stream with end point located lower than the starting point has negative pressure drop due to pressure gained from the elevation change.

4. Case study

The case study shown in Section 2 is solved by applying the heuristics proposed. The stream properties for the case study is shown in Table 1. The pressure at the starting point of the stream (P_{start}) and the pressure at the end point (P_{end}) are also shown at the last two columns of Table 1. It is assumed that there is no external pumping installed at the process stream.

Table 1: Stream properties, P_{start}, and P_{end}

Stream	M (kg/s)	V (m³/s)	h (kW/m².°C)	ρ (kg/m³)	μ (kg/m.s)	C_p (J/kg.°C)	P_{start} (kPa)	P_{end} (kPa)
H1	9.05	0.013	0.2	716	2.4×10^{-4}	1658	800.00	587.29
H2	9.31	0.012	0.2	777	2.3×10^{-4}	2684	720.00	343.48
C1	8.14	0.012	0.2	700	2.3×10^{-4}	2456	400.00	459.75
C2	13.22	0.019	0.2	680	2.3×10^{-4}	2270	650.00	478.41
CU	-		1.5	-	-	-	-	-
HU	-		2.5	-	-	-	-	-

The matching of streams for this case study is determined by prioritising the Pinch rules and some thermodynamic-based retrofit heuristics (Lai et al., 2018) as the plant size is quite small. Figure 2 shows the retrofit design for the case study.
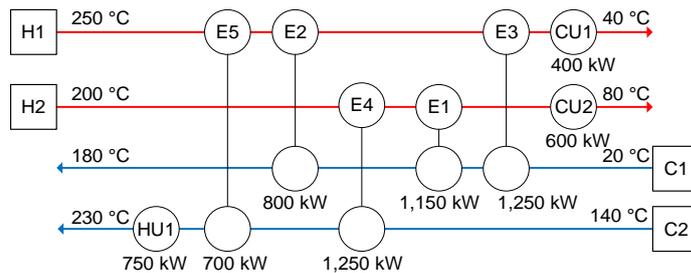

Figure 2: Retrofit design

After matching the streams, the coordinate representation is utilised for heat exchanger placement (see Figure 3). New matches at exchanger E3 and E4 are on the same side of the building. Only the new match at exchanger E5 matches the stream from different buildings. In this work, it is assumed that only the space for the existing heat exchangers is occupied. For other cases, the space availability can be marked on the coordinate.
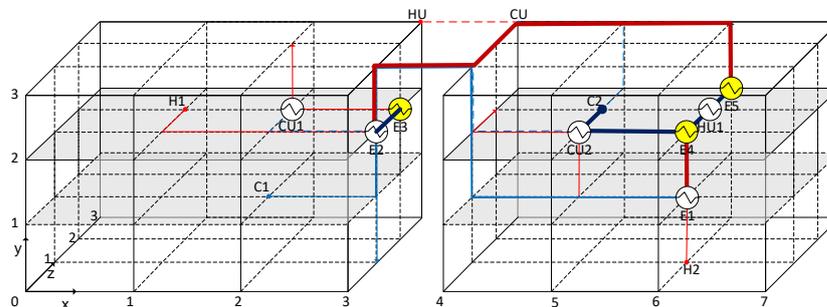

Figure 3: Coordinate representation of retrofit design

Based on Figure 3, heat exchanger E3 which matches stream H1 and C1 is placed near to hot stream H1. Stream H1 has positive existing pressure drop while stream C1 has negative existing pressure drop. According to Heuristic 5, the negative pressure drop at stream C1 can be used to move the process stream towards stream

H1. Furthermore, the volumetric flowrate at stream C1 is smaller than that of stream H1, hence the required additional piping at stream C1 is cheaper due to smaller pipe diameter (Heuristic 2). The additional piping is indicated by bold lines in Figure 3. Heat exchanger E4 matches stream H2 and C2. The volumetric flowrate of stream C2 is larger than that of stream H2, hence exchanger E4 is placed near to stream C2 (Heuristic 2). Heat exchanger E5 matches stream H1 and C2. Exchanger E5 is placed near to stream C2 due to its larger volumetric flowrate as compared to stream H1. Heuristic 3 is not followed in this case study as there is no process stream with extremely high viscosity. For this simple case study, the pumping head limit for each process stream is not provided, hence Heuristic 4 is not considered. The retrofit design for this case study can be different if the pumping head limit is considered.

4.1 Pressure drop calculations and economic analysis

The retrofit pressure drop is calculated for economic analysis. ΔP_f for the additional piping is calculated using the Darcy-Weisbach equation (Gas Processing Supplier Association, 1998). It is assumed that iron cast pipe is used for the piping in this work. The absolute roughness of the pipe (ε) is 0.26 mm, pipe internal diameter (d) is 150 mm, and the Moody friction factor (f_m) obtained from the Moody chart is 0.0225. ΔP_{HE} is assumed to be 34.47 kPa (5 psi) for low-viscosity liquid (Seider et al., 2010) while ΔP_{CV} is neglected. The retrofit pressure drop for the retrofit design is shown in Table 2.

Table 2: Retrofit pressure drop

Stream	$\Delta P_{Retrofit}$(kPa)	$\Delta P_{Existing}$(kPa)	$\Delta P_{Additional}$(kPa)	$L_{Additional}$ (m)
H1	289.34	212.71	76.63	280
H2	412.06	376.52	35.544	40
C1	-24.37	-59.75	35.38	40
C2	246.70	171.59	75.11	100

The capital cost calculation includes the cost of new heat exchangers, pumps, and piping. The cost of pipe is $34.5/ft. The capital cost of new heat exchanger is calculated using Eq(1) while for the pump using Eq(2) (Soltani and Shafiei, 2011).

$$\text{Heat exchanger capital cost (\$)} = 30{,}000 + 750A^{0.81} \tag{1}$$

where A is the heat exchanger area in m².

$$\text{Pump capital cost (\$)} = 2{,}000 + 5(M\Delta P/\rho)^{0.81} \tag{2}$$

where ΔP is the pressure drop that needs to be overcome in Pa and M is the mass flowrate of the stream in kg/s.

It is assumed that all of the existing pumps have achieved their pumping heat limit, hence new pump is assigned to overcome the $\Delta P_{Additional}$. The utility cost calculation includes the cost for hot and cold utilities, as well as the electricity cost for the pump. The hot utility rate is $120/kW.y while cold utility rate is $10/kW.y. The electricity rate is at $0.15/kWh. The annual working hour for this case study is 8,760 h. The annualised factor applied is 0.1175. Table 3 shows the comparison of results before and after considering the plant-layout factor.

Table 3: Comparison of results before and after considering the plant-layout factor

Case	Without considering plant-layout factors	Considering plant-layout factors
Annualised capital cost ($/y)	89,644	86,323
Annualised utility cost ($/y)	130,591	127,500
Total annualised cost ($/y)	220,235	213,824
Savings ($/y)	250,787	253,500
Payback period (y)	3.04	2.90

The comparison of results shows that there is 8.80% difference between the total annualised costs for both cases. This shows the importance of considering physical distance, pressure drop, and available space in generating practical HEN retrofit design. The coordinate representation enables designer to decide stream matches with smaller physical distance and to determine the location for heat exchanger placement which leads to lower pumping and piping costs.

5. Conclusions

A coordinate representation has been proposed for HEN retrofit to enable the physical distance, pressure drop, and available space in an existing HEN to be visualised. A set of heuristics has also been proposed to guide HEN retrofit design that will result in lower piping and pumping costs. By having visualisation of the plant layout using the coordinate representation, the practicability of retrofit design can be improved. Future work shall investigate the use of the graphical tool to determine pipeline paths for the chosen heat exchanger location.

Acknowledgements

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