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An Industrial Case Study Application in Synthesising a Feasible Heat Exchanger Network

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Heat exchanger network synthesis (HENS) is an important part in the overall chemical process. HENS links the process flowsheet with the utility system and generally involves a large fraction of both the overall plant capital cost, operating costs in terms of energy requirements, which is a key factor for a profitable process. The aims of the synthesis consist of finding a network design that minimises the total annualised cost, i.e. the investment cost in units and the operating cost in terms of utility consumption. In HENS, the feasibility of the HEN design does not take into consideration. As a consequence, the HEN design may not be able to be implemented into industrial applications. It is essential to check the feasibility of a design before it is being implemented into the industry. The objective of this paper is to present the application of a new flexible and operable heat exchanger network (FNO HEN) methodology in synthesising a feasible heat exchanger network (F-HEN) using an industrial case study. The aim of this work is to verify the existing industrial HEN design in terms of the process design point of view as well as the process feasibility. The existing industrial HEN design is verified in terms of ΔT_{min} value that gives minimum external energy requirement (EER) and heat exchanger area (HEA) as well as simultaneously analyse the feasibility of the HEN design. Using the new developed FNO HEN methodology framework, HEN design target, which is the value of ΔT_{min} is determined in order to obtain the F-HEN design. From process design point of view, ΔT_{min} value determines the size of heat exchanger in the network as well as energy saving. A process simulator is used to check the process feasibility of the HEN designs. With the use of the F-HEN trade-off plot, which is a plot of EER and HEA at different value of ΔT_{min}. with additional of feasibility area, the optimal feasible HEN design which satisfies external energy requirement (operability), heat exchanger area (capital) and process feasibility has been successfully determined in an easy, systematic and efficient manner.

1. Introductions

There are several methods in Pinch Analysis (PA) concept, such as graphical method, numerical method and mathematical programming method. In graphical method, Wan Alwi and Manan (2010) have modified the conventional graphic method by proposing Steam Temperature versus Enthalpy Plot (STEP). In numerical method, Escobar et al. (2013) proposed framework using numerical concept to synthesis HENs with operability considerations using computational efficiency. In mathematical modelling, Supiluck and Kitipat (2015) work on model formulations in finding effectiveness of initialisation strategy for both HEN synthesis and retrofit design.

The concept of these methods is the same which is to find the optimal (target design) heat exchanger networks that can minimise the usage of heating and cooling utilities, as well as maximising the energy exchange among the process streams. Although there are many methods to fulfil the objective of PA however, feasibility and implementation to real industry can be questionable. It is needed to check the feasibility of a designed HEN (Abu Bakar et al., 2016).

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The objective of this case study is to verify the existing industrial HEN design in terms of the process design point of view as well as the process feasibility. The existing industrial HEN design is verified in terms of ΔT_{min} value that gives the minimum value of HEA and EER as well as simultaneously verified the feasibility of the HEN design (Abu Bakar et al., 2015b).

2. Methodology

2.1 Process Descriptions

The case study is adapted from Abu Bakar et al. (2015a) Fatty acid fractionation plant (FAFP). Figure 1 shows process flow diagram of the FAFP that used in this case study and Table 1 summarises the operating data for the process.

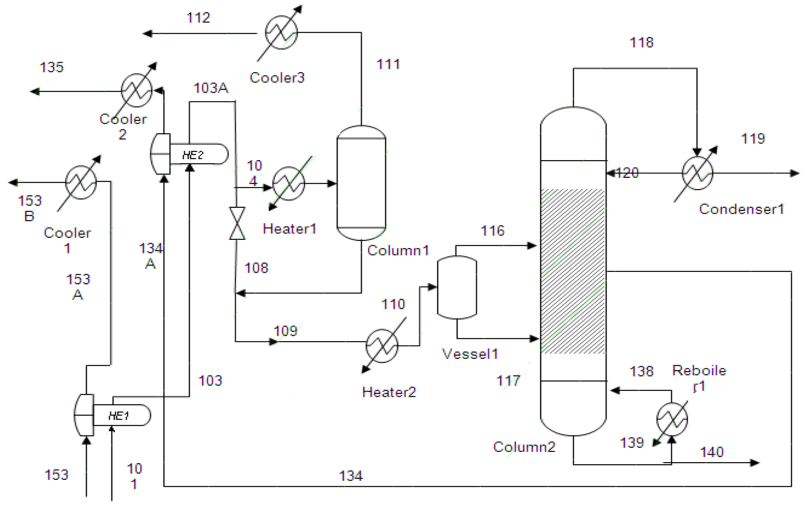

Figure 1: Heat exchanger network (HEN) for fatty acid fractionation plant (Abu Bakar et al., 2015a)

Table 1: Extracted data from the FAFP adapted from initial analysis of Abu Bakar et al. (2015a)

Streams	Stream names		Temperature (°C)		C_p	Flowrate	ΔTemp	FC_p
Type	Inlet	Outlet	Supply	Target	(kJ/kg.K)	(kg/h)	(°C)	(kJ/K)
H1	111	105	128	60	1.882	101	68	190.08
H2	153	153B	140	65	2.176	14,657	75	31,893.63
H3	134	135	209	65	2.553	7,000	144	17,871.00
C1	101	105	70	130	2.053	37,000	60	75,961.00
C2	109	110	128	193	2.205	22,817	65	50,311.49

2.2 Problem statement

The feasible HENs-synthesis problem for this industrial HEN design can be stated as follows:

Given three hot streams (to be cooled) and two cold streams (to be heated), it is desired to synthesise a feasible network of heat exchangers that can transfer heat from the hot streams to the cold streams. Given also the heat capacity flow rate (flow rate x specific heat) of each process hot stream, $FC_{P,u}$; its supply (inlet) temperature, T_u^s; and its target (outlet) temperature, T_u^t, where u = 1, 2, 3. The heat capacity, $fc_{P,v}$, and supply and target temperatures, t_v^s and t_v^t, are given for each process cold stream, where v = 1, 2. In this feasible HENs-synthesis problem statement, focus is given to verify either the real industrial HEN design is optimal and feasible or not where the control structure are assumed to be fixed.

In order to solve the problem statement stated above, method from (Abu Bakar et al., 2015a) has been adapted. Because in this case study the control structure has been assumed to be fixed, only Design Target, HEN Design analysis and Feasible Test were considered. Multi-objective function in the method has been redefined as shown in Eq(1),

$$\max(J) = w_1(P_{1,1}) + w_3\left(\frac{1}{P_{3,3}}\right) + w_3(1/P_{3,2}) \tag{1}$$

- To achieve the process design objective, $P_{1,1}$ is maximised. $P_{1,1}$ is the performance criteria in maximising the energy recovery of the network

- To achieve the steady state sensitivity objective, $P_{2,1}$ is maximised, $P_{2,2}$ is minimised and $P_{2,3}$ is maximised. $P_{2,1}$ is the flexibility, percentage of manipulated variables toleration, while $P_{2,2}$ is the sensitivity of controlled variable, y with respect to disturbance variable, d and $P_{2,3}$ is the controller structure pairing gain, the sensitivity of controlled variable, y with respect to manipulated variable, u.
- To achieve the economic objective, $P_{3,j}$ is minimised. $P_{3,1}$ is the capital cost and $P_{3,2}$ is the operating cost.
- w_1, w_2 and w_3 are weight factors for each objective function to determine optimum value J

2.3 Feasibility Test

All results obtained from Design Target and HEN Design Analysis stages were verified in terms of process design feasibility using process simulator. The output from Stage 2 is the output temperatures from all heat exchangers.

Information transfer from GD to process simulator:

1. Temperature out from GD is transferred to simulator. However, heat exchanger in the process simulator, only required one degree of freedom (one variables value). The other temperature out is automatically calculated by the simulator.
2. Information temperature out obtain from GD may not be the same from process simulator calculation because of the C_p value. C_p value that obtained from GD is assumed the same after temperature has changed but C_p value in the simulator changed as temperature changes.

There are two steps to do in the Feasibility Test. Firstly, is by calculating and analysing the ft correction factor for each heat exchanger in the network. ft correction factors lower than 0.75 it is considered as infeasible. Secondly by observing warning given in the Aspen HYSYS.

Results from the process simulator for HEN design at ΔT_{min} = 10 °C show that heat exchanger HE3 has ft correction factor low problem and have to be redesigned. The yellow warning on the heat exchanger icon (in simulator) indicates that the heat exchanger has ft correction factor low problem. It can be concluded that HEN design at ΔT_{min} = 10 °C is not feasible from the process simulator point of view. The analysis should go back to Design Target stage to choose new value of $\Delta T_{min.}$ with increment 10 °C. Then, HEN at ΔT_{min} at 20 °C, 30 °C, and 40 °C were synthesised, however the feasibility of those candidates is still a question and it needs to be analysed.

3. Results and Discussions

3.1 Difference between the Original HEN and New HEN

After Feasibility Test has been done, the only HEN that are feasible is HEN at ΔT_{min} at 40 °C. From the HEN of ΔT_{min} = 40 °C, that there are two different networks can be generated. These two different networks were obtained since one of the HEN designs was not following the Pinch Analysis (PA) stream splitting rules. It can be seen that the streams in the original HEN (Figure 2) do not have stream splitting while one of the streams in the new HEN (Figure 3) had split into three other streams. Red boxes in both figures show the different arrangement between the original and new HEN arrangements.

Further details of the differences are tabulated in Table 2. There are two different criteria between both candidates: number of heat exchangers and HEA. The original HEN has less heat exchangers (two heat exchangers) compared to the new HEN (four heat exchangers). For the HEA, the new HEN has smaller value than the original HEN. From this result, it will be difficult to decide which network design is the best. Therefore, multi-objective function was calculated to select the best design using Eq(1).

Table 2: Criteria of original HEN and new HEN designs at ΔT_{min} = 40 °C

Criteria	Original HEN	New HEN
PA matching rules	Not followed	Followed
Number of Heat Exchanger	2	4
No of heater	2	2
No of cooler	3	3
Splitting	No	Yes
EER value (kW)	1,606.5	1,606.5
HEA value (m^2)	46.3	42.4
PFD	Figure 2	Figure 3

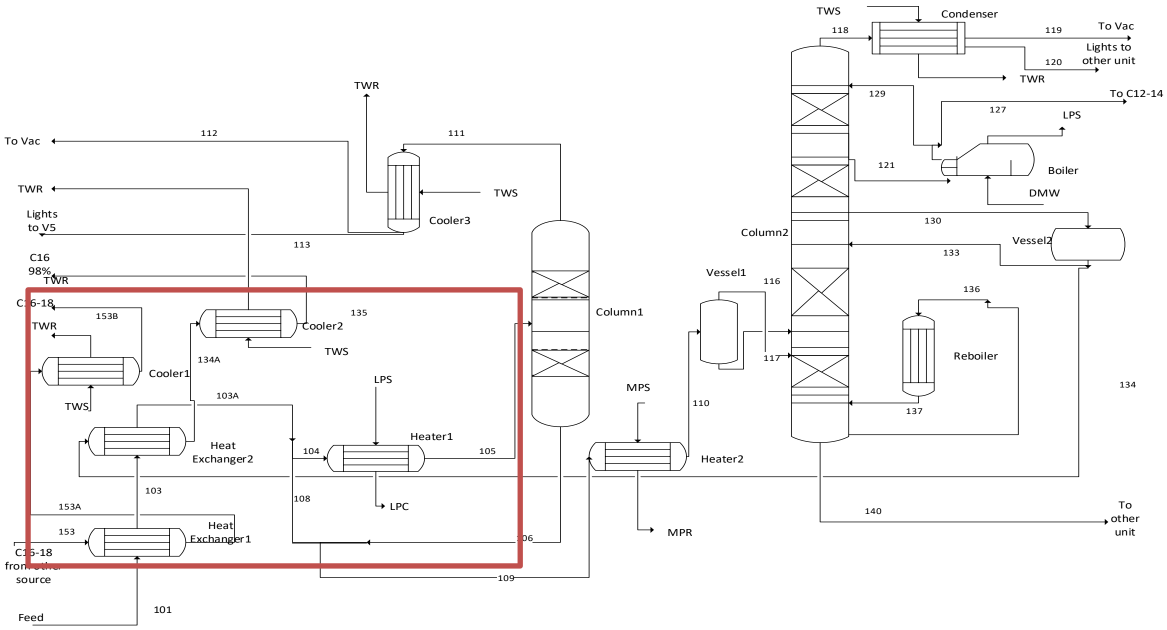

Figure 2: Process flow diagram of original HEN for a unit in FAFP

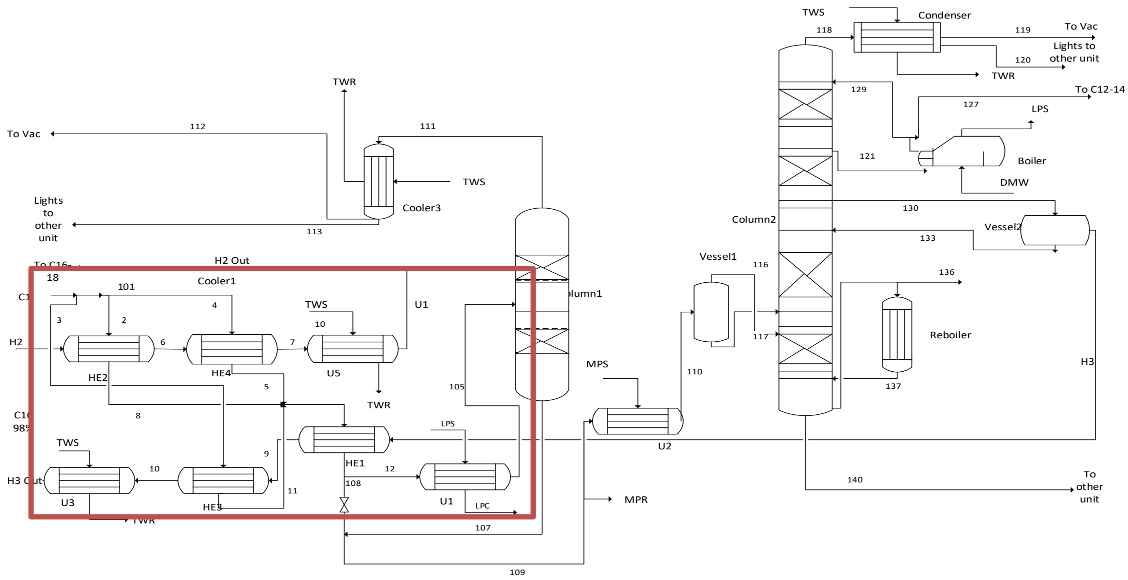

Figure 3: Process flow diagram of new HEN for a unit in FAFP

3.2 Multi-objectives function calculation

All objective function values were collected from Design Target and HEN Design Analysis stages and tabulated and results of multi-objective functions is presented in Table 3. Since all the values of the objective functions have different units, therefore all objective function values need to be normalised by dividing it with the largest value of each objective functions (Abu Bakar et al., 2013). Then, using the normalised objective function values, the value multi-objective J is calculated using Eq(1) for both new HEN and original HEN. It can be seen that the new HEN design has the highest value of the multi-objective function is the new HEN design that follows the PA matching rules. It is important for HEN design to follow PA rules in order to get the optimal HEN design.

Table 3: Multi-objective function calculation of Case Study 2

	Maximum Energy Recovery (MER) (kW)	Heat Exchange Area (HEA) (m^2)	External Energy Requirement (EER) (kW)
Design/Control value, $P_{x,x}$	$P_{1,1}$	$P_{3,1}$	$P_{3,2}$
New HEN	734.650	42.383	1,606.484
Original HEN	734.650	46.324	1,606.485
Normalise value, $P_{x,xs}$	$P_{1,1s}$	$P_{3,1s}$	$P_{3,2s}$
New HEN	1.000	0.915	1.000
Original HEN	1.000	1.000	1.000
Multi-objective function value,	$P_{1,1}$	$1/P_{3,1s}$	$1/P_{3,2s}$
New HEN	1.000	1.093	1.000
Original HEN	1.000	1.000	1.000

3.3 F-HEN Trade-Off Plot

The F-HEN trade-off plot is a plot of EER and HEA at different value of ΔT_{min} with additional of feasibility area (Figure 4). From the figure, the best HEN candidate (in terms of EER and HEA) that satisfies the design criteria can be identified at the intersection point between EER and HEA lines, which is approximately at ΔT_{min} = 32 °C. The similar concept also has been used by Dimian et al. (2014) to identify the optimal HEN design using common trade-off plot which energy and capital cost versus ΔT_{min}.

The optimal HEN design is not located inside the feasible area (Figure 4). It can be clearly seen that the feasible area for this case study is ΔT_{min} = 40 °C and above. Since the optimal HEN design is located outside the feasible area, it can be concluded that the optimal HEN design at ΔT_{min} = 32 °C is not feasible. It must be noted here that, the identification of the feasible area was based on the ΔT_{min} = 10 °C increment, which can be considered as too large for this analysis. This large increment value has a large possibility to overlook the optimal feasible design solution. The question either the design value at ΔT_{min} = 32 °C is feasible or not, still needs to be answered. For this reason, the feasibility analysis needs to be extended at ΔT_{min} = 32 °C. The results of the extended feasibility analysis have shown that the HEN ΔT_{min} = 32 °C is not feasible. Therefore, the cross point at 32 °C is still not in the feasible region.

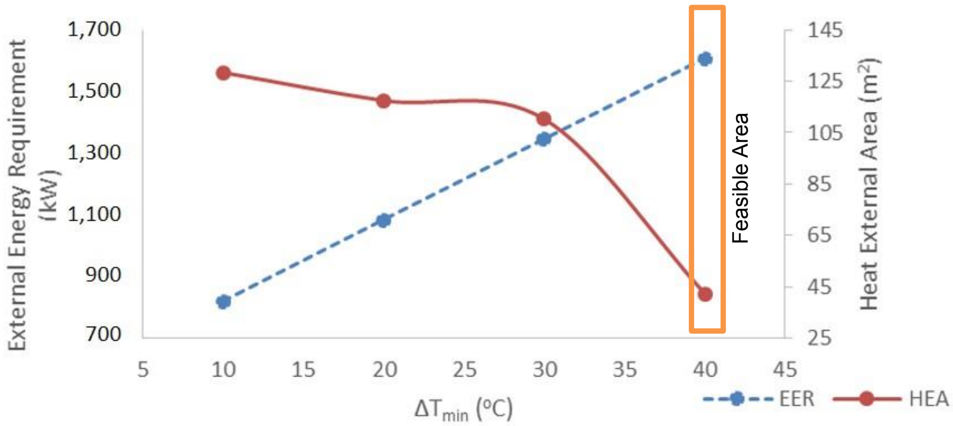

Figure 4: HEN trade-off plot with feasibility area for Case Study

4. Conclusions

The existing industrial HEN design has been verified in terms of ΔT_{min} value that gives the minimum value of HEA and EER as well as simultaneously verified the feasibility of the HEN design. Throughout this case study, the HEN design that follows PA matching rules gives the best design results compared with the one that is not following the rules. The optimal solution for the feasible HEN design of the case study which satisfies external energy requirement (operability), heat exchanger area (capital) and process feasibility has been successfully analysed in this section using the developed FNO HEN methodology framework. The use of feasible trade-off plot helps in obtaining the optimal feasible HEN design in efficient and systematic manner.

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