Sensitivity Analysis of Industrial Heat Exchanger Network Design

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The problem of interaction between economic design and controller design of heat exchanger network (HEN) is addressed in this work. The feasibility and sensitivity issues are incorporated in the classical design of HEN. HENs in industry seem to be very efficiently operated. The network that may have operated efficiently perhaps is the one that is not fully optimised in term of flexibility and sensitivity. It is important to do synthesis and sensitivity analyses of the designed network. The objective of this paper is to investigate and compare the sensitivity criteria of the originally designed HEN of the fatty acid fractionation process (FAFP) and the new HEN design. In this study, the HEN designs are already fixed at the value of ΔT_{min} = 40 °C. A new suggested HEN is redesigned from the original HEN of FAFP plant by obeying Pinch Analysis (PA) rules. The new HEN was redesigned by applying the PA stream splitting compared to the original HEN (that has been used in the industry), in which the design is not have stream splitting. The aim of this work is to determine the best optimised design whether the one that not followed Pinch Analysis rules or the other one. Using the new developed FNO HEN methodology framework, sensitivity analysis was applied which consists of two tests: 1) Flexibility Analysis and 2) Sensitivity Analysis. According to the results, the best candidate that satisfies the sensitivity and economy criteria is the new HEN design. It can be concluded that it is important to do stream splitting in order to obtain not only the best HEN in terms of design and economy criteria, but also in the matter of sensitivity criteria.

1. Introduction

Synthesis of heat exchanger network (HEN) has been an important research field as it is one of the main criteria to optimise energy in process industries. Improve economic side of process industries. There are lots of research to improve synthesis of HEN. However the synthesis of a cost-effective HEN design focus on aiming to maximise heat recovery by considering the trade-off between the capital and operating costs for a given value of ΔT_{min}. Sarut and Kitipat(2014) considered minimisation of total annual cost (TAC) of freshwater cost, piping cost, investment cost of heat exchanger unit, and hot/cold utility cost. The research solve the optimisation problem based on mathematical programming for simultaneous water and heat exchanger network design of fixed-flowrate system. Sun et al. (2013) investigated the effect of ΔT_{min} contribution on cost, by considering multiple utilities. The research is by stream temperature vs. enthalpy plot supertargeting method. Akbarnia et al. (2009) applied PA to do super targeting by considering piping cost, materials of construction and pressure rating. The research just focus on reducing design and operational cost only.

Kravanja and Glavi (1997) performed cost targeting on a heat exchanger network using a combination of PA and a complex algorithmic approach. They combined *PA* with the complex algorithmic approach to target cost and to reduce feasibility region defined over sets of discretised decision variables. The problem of interaction between economic design and controller design of HEN is addressed in this work. The feasibility and sensitivity issues are incorporated in the classical design of HEN. HEN in industry seem to be very efficiently operated. The network that may have operated efficiently perhaps is the one that is not fully optimised. The

latest, Kang et al. (2016) have consider multi period heat exchanger network based on sub-period durations, however the solution is based on total annual cost. Zhang et al. (2016) had done research on synthesis large-scale heat exchanger network. The method to solve the problem is by using algorithm that combines deterministic and stochastic optimisations to obtain an optimal sub-network. In that case, the objective function is to minimise TAC.

The sole solution of synthesis HEN is to minimise TAC. There is not many research on synthesis HEN and considering sensitivity analysis simultaneously. The objective of this paper is to evaluate the feasible HEN designs section in terms of analyses the HEN sensitivity. Two types of sensitivity analyses were evaluated: process flexibility ($P_{2,1}$) and process sensitivity ($P_{2,2}$). It should be noted that the controller structure selection ($P_{2,3}$) was not evaluated in this stage since all the output temperatures (controlled variables) are already been paired with the flow rates of the external utilities.

2. Methodology

2.1 Problem statement

The sensitivity heat exchanger network (S-HEN) problem can be stated as follows:

Given three hot streams (to be cooled) and two cold streams (to be heated), it is desired to investigate the sensitivity of the synthesised heat exchanger network that can transfer heat from the hot streams to the cold streams. Given also the heat capacity, $C_{P,u}$; and flow rate, F of each process hot stream, its supply (inlet) temperature, T_u^s; and its target (outlet) temperature, T_u^t, where u = 1, 2, 3. Given 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 case, the HEN designs are already fixed at the value of ΔT_{min} = 40 °C and focus is given to investigate the sensitivity for the original HEN and the new suggested HEN designs as shown in Figure 1.

2.2 Problem definition

For this case study, all the stages of FNO HEN methodology framework as adapted from Abu Bakar et. al., (2015b) are implemented. As defined in the previous subsection, the HEN design for this case study is assumed to be fixed at ΔT_{min} = 40 °C. Multi-objective function is adapted from Abu Bakar et al. (2013). Since the HEN design already fixed, therefore weight factor for design analysis objective function, w_1 is set as zero, therefore the multi-objective function is redefined based on the problem statement. The new defined multi-objectives function is shown in Eq(1).

$$\max(J) = w_2 P_{2,1} + w_2 \left(1/P_{2,2}\right) + w_2 \left(P_{2,3}\right) + w_3 \left(1/P_{3,1}\right) + w_3 \left(1/P_{3,2}\right) \tag{1}$$

- 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_2 and w_3 are weight factors for each objective function to determine optimum value J.

3. Sensitivity design analysis

3.1 Flexibility analysis

Flexibility (F) test can be defined as capability of the network to tolerate the maximum changes of manipulated variables (u). Flexibility analysis is evaluated by calculating the percentage changes of the manipulated variables (feed flow rates) that can be tolerated by each feasible HENs (refer Eq(2)). The network that has the highest percentage changes in all network streams is regarded as the most flexible HEN design. This test can be performed by increasing the value of one of the manipulated variables. The next step is to observe if there is any operation warning in any heat exchanger within the network. For example, one of the feed stream flow rate (F_{H1}) is adjusted and its value is increased until the operation warning either 'temperature cross' or 'ft correction factors is low' is observed. Once the operation warning is observed, the previous increment value is considered as the maximum value of the flow rate, and then the percentage is calculated. This procedure is repeated for all manipulated variables in the network. Then, the averages of percentage changes for all feed streams were calculated using Eq(2). The highest average was selected as the most flexible network.

$$F = \frac{\sum_{i=1}^{i=n} u\,\%}{n} \tag{2}$$

The results of the flexibility test are summarised in Table 1. The original designed HEN has a flexibility of 79.51 % whereas the new designed HEN has a flexibility of 82.52 %.
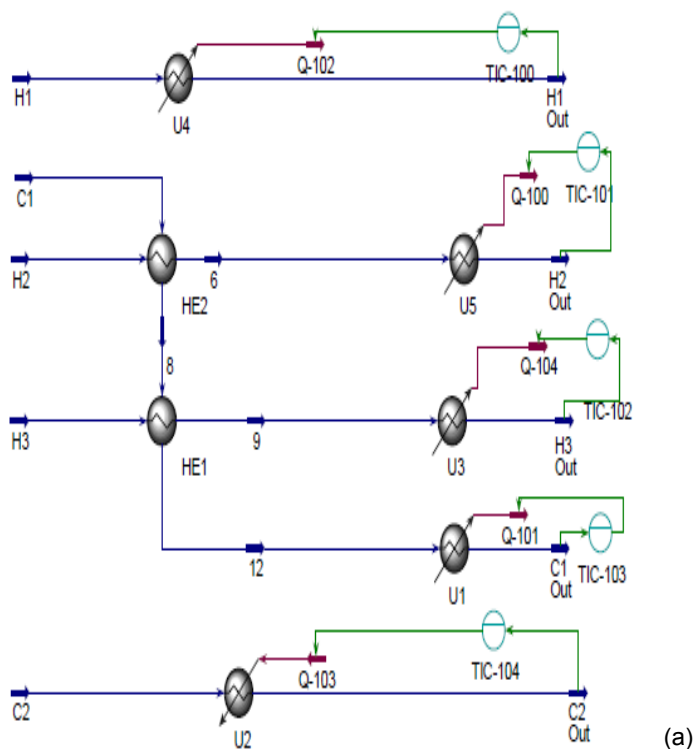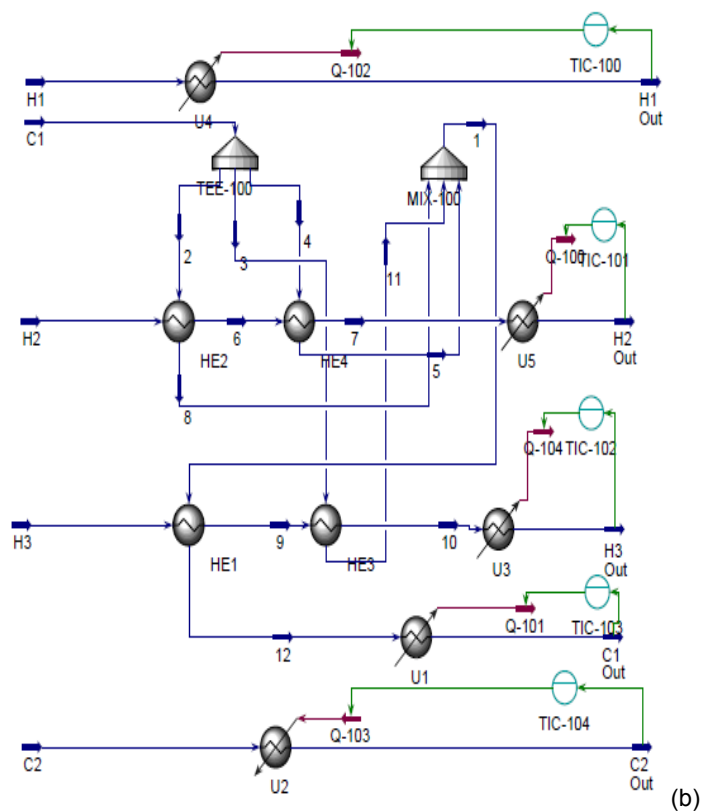
Figure 1: Aspen HYSYS simulation environment for (a) original designed HEN, (b) new designed HEN (Abu Bakar et al., 2015a)

Table 1: Flexibility results of the HEN designs

U	Original HEN	New HEN
ΔT_{min}		
F_{H1}(%)	100	100
F_{H2}(%)	100	36.13
F_{H3} (%)	100	76.16
F_{C1}(%)	0.60	100
F_{C2} (%)	96.93	100
Average	79.51	82.46

3.2 Sensitivity analysis

The sensitivity analysis was implemented to measure the minimum effect of the controlled variables (stream temperature outputs) (*y*) or the minimum effect that the designed *HEN*s can resist (minimum effect towards operational warnings) with respect to disturbance variables (feed temperatures) (*d*). Then, the derivative of the controlled variable with respect to disturbance is calculated (*dy/dd*) and the minimum of *dy/dd* is considered as the best option.

$$s = \frac{\sum_{i=1}^{i=n} \frac{dy_i}{dd_i}}{n} \tag{3}$$

In this case study, since all the output temperatures (controlled variables) are already controlled by manipulating the external utilities (Figure 1), the sensitivity analysis was done to measure the minimum effect towards operational warnings that the designed *HEN*s can resist with respect to the changes in disturbance variables. This analysis can be performed by increasing the value of one of the disturbance variables. The next step is to observe if there is any operation warning in any heat exchanger within the network. For example, one of the disturbance variables (T_{H1}) is adjusted and its value is increased until the operation warning either 'temperature cross' or '*ft correction factors* is low' is observed. Once the operation warning is observed, the previous increment value is considered as the maximum value of the feed temperature, and then the percentage is calculated. This procedure is repeated for all disturbance variables in the network. Then, the averages of percentage changes for all feed temperatures were calculated. The results of sensitivity analysis are summarised in Table 2. The average tolerable changes of disturbance variables for a new designed HEN is about 48.21 %, whereas for the original HEN, it was found that this design is more sensitive to the changes of disturbance variables, with average sensitivity of 60 %.

3.3 Optimal selection and verification

For the economic analysis, the calculation for the capital cost is assumed to be a function of heat exchange area (HEA), while the calculation for the operating cost is assumed to be a function of external energy requirement (EER). Since the design has been fixed at ΔT_{min} = 40 °C, the results of HEA and EER for both design is the same as shown in Table 3.

Table 2: Sensitivity results of the original and new designed HENs

Design	Original HEN	New HEN
U		
T_{H1}(%)	100	85.71
T_{H2} (%)	0	0
T_{H3}(%)	0	0
T_{C1}(%)	100	87.86
T_{C2} (%)	100	67.46
Average	60	48.21

Table 3: Value of ft correction factor and status of HEN design candidates

No	*HEN* Design Name	Heat transfer area (m^2)	Operating duties (kW)
1	Original *HEN*	46.32	1606.49
2	New *HEN*	42.38	1606.48

3.4 Multi-objectives function

All objective function values were collected from Stage 3 and Stage 4 and tabulated in Table 4. Both candidates were then validated by calculating the multi-objective function using Eq(1). Before calculating the multi-objective function, the value of the objective function needs to be normalised. Since all the values of the objective functions have different range and unit, therefore all objective function values need to be normalised with respect to its maximum value. In study, all the objective function terms are weighted equally, so that the decision-maker does not have any preference for one objective over another. The largest J value which is in bold shows the best overall candidate for this case study. The results of the multi-objective function calculation in Table 4 prove that the new HEN design resulted in the maximum J value.

Table 4: Multi-objective function calculation of the designed HEN candidates

	Flexibility (control)	Sensitivity (control)	Capital Cost (design) (m^2)	Operating cost (design) (kW)	
Design/Control value, $P_{x,x}$	$P_{2,1}$	$P_{2,2}$	$P_{3,1}$	$P_{3,2}$	
Original *HEN*	79.51	60	46.32	1606.49	
New *HEN*	82.46	48.21	42.38	1606.48	
Normalise value, $P_{x,xs}$	$P_{2,1s}$	$P_{2,2s}$	$P_{3,1s}$	$P_{3,2s}$	
Original *HEN*	0.96	1	1	1	
New *HEN*	1	0.8	0.92	1	
Multi-objective function value,	$P_{2,1s}$	$1/P_{2,2s}$	$1/P_{3,1s}$	$1/P_{3,2s}$	J
Original *HEN*	0.96	1	1	1	3.96
New *HEN*	1	1.25	1.09	1	4.34

3.5 Sensitivity HEN trade-off plot

The sensitivity criteria analysis of HEN consists of feasibility and sensitivity tests as shown in Figure 2. In the figure, design number 1 represents the original HEN design while design number 2 represents the new HEN design. It can be clearly seen that the original HEN (design number 1) has a smaller feasibility (blue dot) compared to the new HEN design (design number 2). In terms of the sensitivity criteria (red dot), the original HEN has a higher value compared to the new HEN.

According to the FNO HEN methodology framework, from the process control point of view, the design candidate with the highest flexibility value is the optimal one. This is because it is more robust and capable in maintaining the sensitively variables with higher flow rate. HEN design with higher sensitivity criteria is not a good design since it will be too sensitive to the smaller changes in disturbances, hence making it very difficult to be controlled. The optimal network from operation point of view is the one that has smaller sensitivity criteria with higher flexibility criteria.
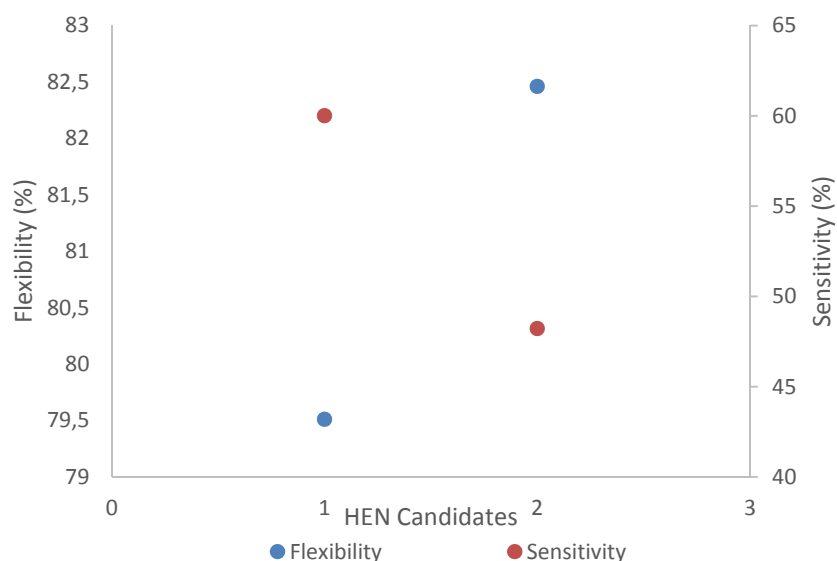

Figure 2: Flexibility and sensitivity analysis of two different HEN designs

4. Conclusion

The investigation on the sensitivity HEN (S-HEN) of the FAFP case study has been successfully done using FNO HEN methodology framework. Although the process design criteria have been fixed in the beginning of this case study, from the process design results, two different HENs have been obtained in this research. Based on these two designs, the sensitivity criteria have been performed for both design candidates. From the results, the best candidate that satisfies the sensitivity and economy criteria is the new HEN design. According to process design point of view, the new HEN was designed by applying the PA stream splitting compared to the original HEN (that has been used in the industry), which its design does not have stream splitting. It can be concluded that it is important to do stream splitting in order to obtain not only the best HEN in terms of design and economy criteria, but also in the matter of sensitivity criteria.

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