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A New Systematic Method for Optimal Heat Recovery Networks Design with Minimum Area and Exergy Loss

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Abstract: This study presents a new systematic technique for design of heat recovery network with minimum area and exergy loss. This method uses payback period as the decision variable to decide the best hot and cold stream matches. Based on the payback period, the minimum heat exchanger networks area which yields the minimum exergy loss will be obtained. The proposed technique begins with the construction of segregated curves on a temperature versus heat load diagram for all process streams to give preliminary information of all possible stream matches. The next step is to set up decision stream match table which uses payback period as the decision variable for streams matching. The final step of the procedure involves optimization the heat exchanger loops and paths. Application of the approach on a case study shows that better results can be achieved in terms of the total cost, utility cost, heat exchanger networks area and exergy loss as compared to the results obtained using conventional Pinch Technique.

Key words: Exergy consumption, heat exchanger networks area, pinch analysis technique

INTRODUCTION

Many researches have been focused on the design of Heat Exchanger Networks (HEN) for efficient energy management. In order to design a HEN to achieve the minimum total cost, one has to consider the costs of heat exchanger area, utilities and exergy loss. Previous researchers normally design HEN based on Pinch Technique (Linnhoff *et al*., 1983), Mathematical Programming (Floudas *et al*., 1986), Stochastic optimization (Lewin, 1998; Dipama *et al*., 2007) or Exergy Analysis (Kotas, 1995; Lim, 2002; Lim and Manan, 2001; Linnhoff *et al*., 1982). Superstructure approach (Umeda *et al*., 1978) and genetic algorithm approach (Dipama *et al*., 2007) can include all constraints but however is very complex and is not preferred by practicing engineers. Exergy analysis for HEN design (Lim and Manan, 2001; Lim, 2002) which is based on second law of thermodynamic will not minimize heat exchanger area. In the other hand by minimizing exergy loss, heat exchanger area will actually increase.

MATERIALS AND METHODS

The current proposed method consists of several stages (Fig. 1) as described next.

Step 1: Construction of segregated enthalpy vs. temperature curve: In order to construct the Segregate enthalpy vs. temperature curve, the first step is to change the supply and target temperatures of the hot and cold streams (T_h and T_c) to shifted temperatures (T_h^1 and T_c^1) using Eq. 1 and 2:

$$T_h' = T_h - \frac{\Delta T_{min}}{2} \quad (1)$$

$$T_c' = T_c + \frac{\Delta T_{min}}{2} \quad (2)$$

The next step is to draw all the hot and cold streams based on the shifted temperature in the enthalpy vs. temperature plot. The detailed instructions to draw the segregated enthalpy vs. temperature can be found in (Wan Alwi and Abdul Manan, 2009). In order to achieve minimum heat exchanger network area and utility cost, some rules needed to be applied as follow:

- The hot stream which has the biggest heat load is Recommended to be matched first with cold stream which has the biggest heat load
- It is desirable to match the high temperature hot stream with the high temperature cold stream. Similarly, the hot stream with lower temperature is recommended to be matched with cold stream with the lowest temperature. This action will increase the exergy efficiently of the stream

Step 2: Setting up payback period match table: In step 2, the payback period is used as decision variable for the

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stream match. To obtain payback period, Eq. 3 is used. Areas of heat exchangers are calculated using Eq. 4 and exergy consumption using Eq. 5. The heat exchanger bare module cost is calculated based on (Biegler *et al.*, 1997). Assumming operating hours of 8400 h year^{-1}, price of fuel, cooling water and hot oil are 0.00291, \$41.504 and \$169.421 kw^{-1}, respectively, the total cost can be calculated using Eq. 6 and the savings using Eq. 7.

$$\text{Payback period (year)} = \frac{\text{Bare module cost heat exchanger network area}}{\text{Saving}} \quad (3)$$

$$A_{network} = \sum_{k}^{interval k} \frac{1}{\Delta T_{LMK}} \left(\sum_{i}^{hot stream i} \frac{q_{i,k}}{h_i} + \sum_{j}^{cold stream j} \frac{q_{j,k}}{h_j} \right) \quad (4)$$

$$\text{Exergy consumption (kw)} = \Delta H \left[1 - \frac{To}{\Delta Tlm} \right] \quad (5)$$

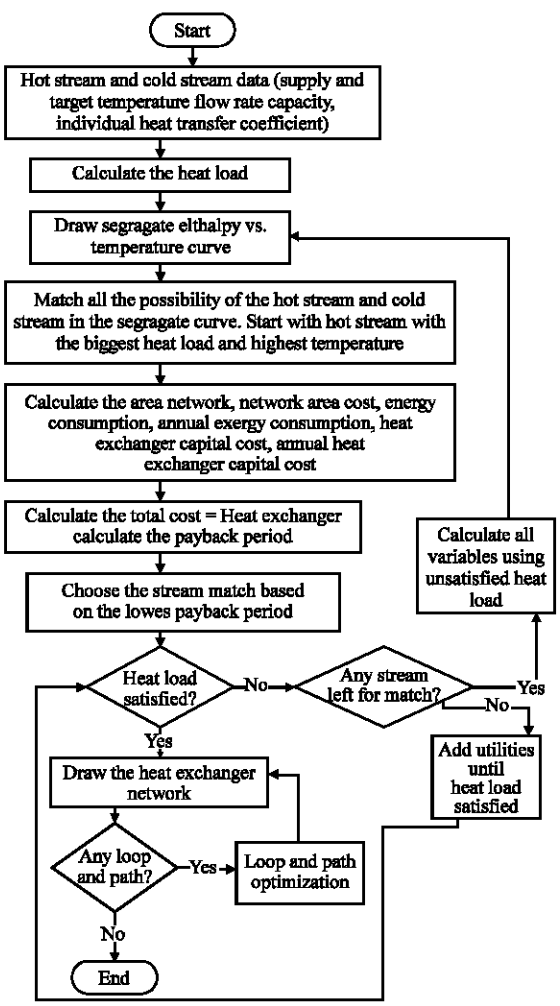

Fig. 1: Method flow chart

$$\text{Total cost (\$ year}^{-1}) = \text{Annual heat exchanger area cost} + \text{annual exergy consumption} + Qc + Qh \quad (6)$$

$$\text{Saving} = \sum_{i}^{hot stream i} Qi \times \text{hot utility cost} + \sum_{j}^{cold stream j} Qj \times \text{cold utility cost} \quad (7)$$

Step 3: Loops and paths optimization: In some cases, the matching process can lead to some load being left unsatisfied in the networks or leaving excessive units with relatively small heat loads. Therefore, further evolution on the networks should be carried out to optimize the networks by reassigning the unsatisfied heat load and minimizing the number of heat exchanger by loop breaking techniques. Details explanation about loop breaking and path optimization are explained by Kemp (2007).

RESULTS

The methodology is tested using the data from (Kemp, 2007) where it consists of three hot and three cold streams. Table 1 shows the stream data with the shifted temperature assuming ΔT_{min} = 10°C. In this stage, the streams matches have not been decided yet.

From the stream data above, the hot and cold streams can be plotted directly to segregate curve. Figure 2 show the preliminary segregate curve of case study 1.

The possible stream match can be gained by applying some rules explained in Step 1. The final segregated curve is shown in Fig. 3.

The next step is to calculate the payback period from all possible matches achieved from the previous step. In order to decide the stream matches with minimum payback period the proposed method use the Payback Period Match Table (PPMT). The PPMT is shown in Table 2. By using the PPMT, information about the minimum payback period for all possible streams matches can be clearly shown.

After choose the smallest payback period for all the streams, the final payback period match table is achieved. As can be seen in Table 3, the stream match which have the minimum payback period are H1 - C1, H2(1) - C2(1), H2(2)-C3 and H3-C2(2).

Table 1: Stream data for study case 1

	h (kw° cm^{-2})	Ts (°C)	Tt (°C)	FCp (kw/°C)	DH (kw)	Ts' (°C)	Tt' (°C)
H1	1.0	250	40	0.15	31.5	245	35
H2	0.8	200	80	0.25	30.0	195	75
H3	3.0	240	239	7.50	7.5	235	234
C1	0.6	20	180	0.20	32.0	25	185
C2	0.8	100	230	0.30	39.0	105	235
C3	1.0	20	30	1.00	10.0	25	35

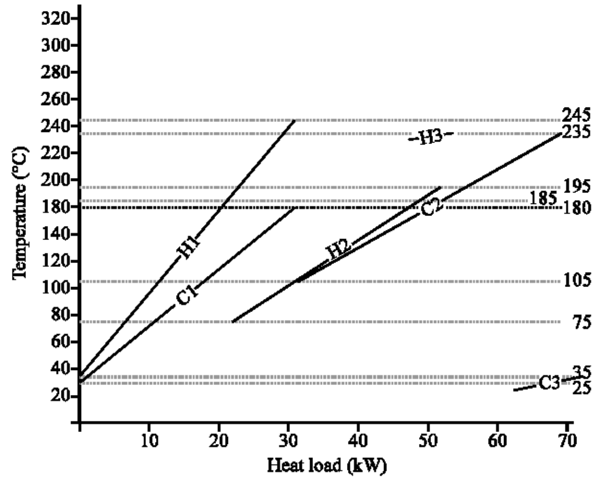

Fig. 2: Preliminary segregated enthalpy vs. temperature curve for case study 1

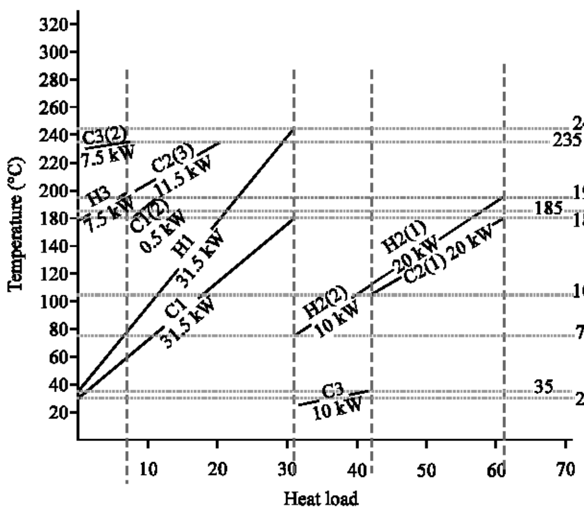

Fig. 3: Final segregated enthalpy vs. temperature curve for case study 1

Table 2: Payback period match table

Stream	C1 (Year)	C2 (Year)	C3 (Year)
H1	0.18	0.26	0.55
Stream	C2(1) (Year)	C3 (Year)	
H2(1)	0.284	0.280	
Stream	C3 (Year)		
H2(2)	0.55		
Stream	C2(2) (Year)	C1(2) (Year)	
H3	0.73	10.32	

Table 3: Final payback period match table

Stream Match	Heat load (KW)	Payback period (year)
H1-C1	31.5	0.18
H2(1) - C2(1)	20.0	0.28
H2(2) - C3	10.0	0.55
H3 - C2(2)	7.5	0.73

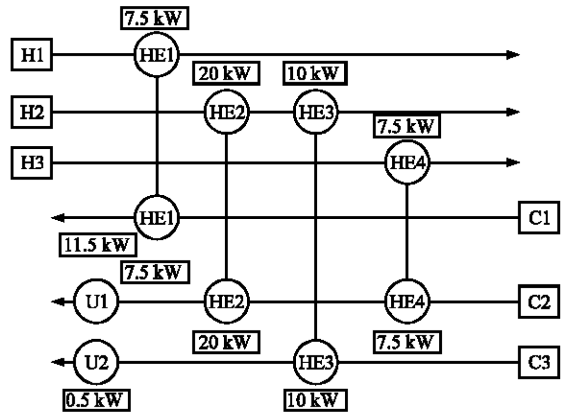

Fig. 4: Heat exchanger network design for case study 1

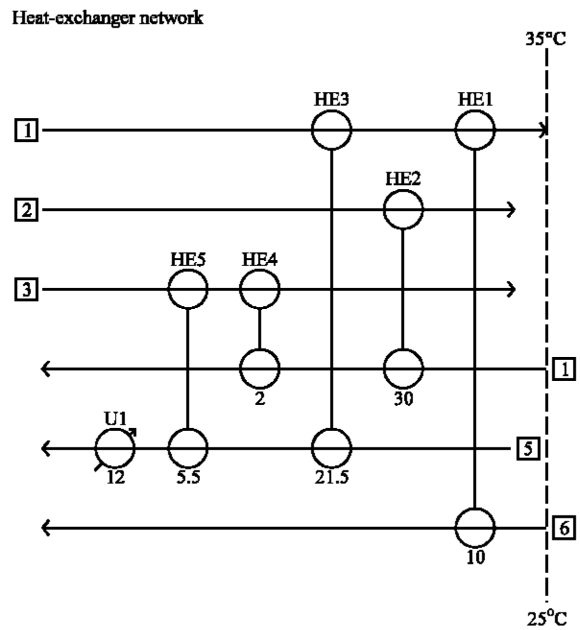

Fig. 5: Final heat exchanger networks design using pinch analysis

Figure 3 describe that there are cold stream left unmatched (12 kW). These cold streams will use additional hot utility to satisfy its entire heat load. The final heat exchanger network design is shown in Fig. 4.

DISCUSSION

In this study, the proposed method results are compared with the results obtained using pinch technique. By using the same case study, the heat exchanger networks obtained is as shown in Fig. 5. The results comparison between proposed method and pinch analysis is shown in Table 3.

Table 4: Comparison result between proposed method and pinch analysis

Method	Utility cost ($/kw)	Heat exchanger area cost ($ year^{-1})	Annual exergy consumption cost ($/kw.year)
Proposed method	498.048 (12 kw)	4738.26 (5.77 ft2) (4HE)	87.78
Pinch	498.048 (12 kw)	5852.64 (5.71 ft2) (5HE)	112.04

As can be seen in Table 4, the heat exchanger area cost as well as exergy loss using the proposed method is lower than the results obtained using pinch analysis.

CONCLUSION

A new systematic method for optimal heat recovery networks design has been introduced. The method minimizes area and exergy consumption for grassroots design.

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