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# Retrofit Design of Heat Exchanger Networks of Crude Distillation Unit

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Due to energy and economic crisis, one way to improve energy efficiency of the refinery having crude distillation units (CDU), high-energy-consuming units, with complex heat exchanger networks (HENs) is to reduce energy consumption at crude furnaces and product coolers. They can be retrofitted by applying pinch analysis (1970s) and stage model by Yee and Grossmann (1990). For the retrofit design with minimal network changes, the stage model and heat-demand-supply diagram by Bagajewicz and Ji (2001) can be applied by fixing the same location of exchangers as the exisiting one and varying the exchanger minimum temperature approach (EMAT) in the model. The result showed that minimal additional exchanger area will be added to recover heat for preheating crude and also increase the furnace inlet temperature, resulting in energy savings at furnace and coolers about 1.3 % and 2.8%, respectively.

## 1. Introduction

Heat exchanger network retrofit of CDU is to modify the existing exchanger network with minimal changes, resulting in energy saving on crude furnaces and product coolers. The modification can be adding new exchangers or more exchanger area to the existing HEN, or relocating the existing exchangers. Yee and Grossmann (1990) used the optimization model called stage model to do the grassroots design of HEN. This research work applied the stage model to do the retrofit design of HEN for CDU from a refinery in Thailand . This CDU is one of the largest energy-consuming units having the crude preheating train or HEN transferring heat from pump-around and hot product streams; naphtha (OVHD), kerosene(KERO), light and heavy gas oil (LGO, HGO), and long residue(LR), to the crude feed (CRUDE) as shown in Fig.1. Preheating the crude by HEN helps reduce fuel consumption at the crude furnace. Currently, it consumes hot and cold utilities about 105.2 and 100.8 MW, respectively.

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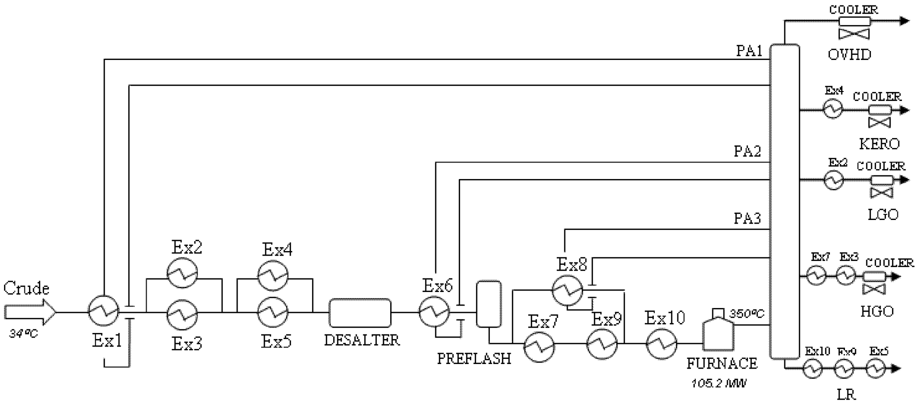

*Figure 1. Existing HEN of crude preheating train*

## 2. Retrofit Potential

Pinch analysis (1970s) was used to check the retrofit potential of the crude preheating train by generating the composite curves of hot and cold process streams as shown in Fig. 2. It shows that the process has minimum temperature difference of 38 °C at the pinch point between 135.7 °C and 173.7 °C, meaning that there is the scope of HEN retrofitting by adding some more exchanger area and/or new exchangers. And the HEN retrofit is done by using the optimization model or stage model (1990).

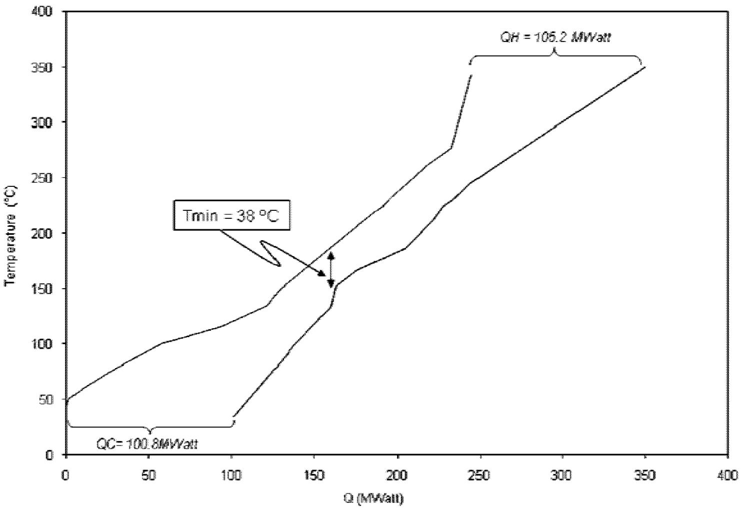

*Figure 2. Composite curves of crude preheating train*

## 3. Stage model

The stage model is based on the stage-wise superstructure representation proposed by Yee et al. (1990) . The structure is shown in Fig. 3. Within each stage of superstructure, possible exchanger between any pair of hot and cold streams can occur. Heater and coolers are placed at the end of cold and hot streams, respectively. The objective function of the model is to minimize the duty of heater, cooler and number of exchangers under the constraint functions of energy balance, thermodynamics, and logical constraints.

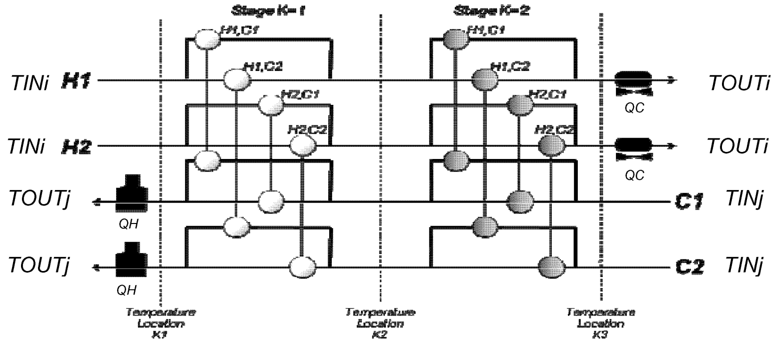

***Figure 3.*** *Two-stage model structure*

The target temperatures and flow rate of hot and cold process streams are fixed and the stage-model will design HEN into two stages (K1 and K2) with the minimum utility usages and number of exchangers for fixed EMAT value. The constraints and objective function of stage model are shown below.

*Overall heat balance for each stream.*

$$(TIN_i - TOUT_i)F_i = \sum_{k\in ST} \sum_{j\in CP} q_{ijk} + qcu_i \qquad i \in HP$$

$$(TOUT_j - TINj)F_j = \sum_{k\in ST} \sum_{i\in HP} q_{ijk} + qhu_j \qquad j \in CP$$

*Heat balance at each stage.*

$$(t_{i,k} - t_{i,k+1})Fi = \sum_{j\in CP} q_{ijk} \qquad k\in ST,\ i\in HP$$

$$(t_{j,k} - t_{j,k+1})Fj = \sum_{i\in CP} q_{ijk} \qquad k\in ST, j\in HP$$

*Assignment of superstructure inlet temperatures.*

$$TIN_i = t_{i,1}$$

$$TIN_j = t_{j,\,NOK+1}$$

*Feasibility of temperatures.*

$$t_{i,k} \le t_{i,k+1} \qquad k\in ST,\ i\in HP$$

$$t_{j,k} \le t_{j,k+1} \qquad k\in ST, j\in CP$$

$$TOUT_i \le t_{i,NOK+1} \qquad i\in HP$$

$$TOUT_j \le t_{j,1} \qquad j\in CP$$

*Hot and cold utility load.*

$$(t_{i,NOK+1} - TOUT_i)\ Fi = qcu_i \qquad i\in HP$$

$$(TOUT_j - t_{i,1})\ F_j = qhu_j \qquad j\in CP$$

*Logical constraints.*

$$q_{ijk} - \Omega\, z_{ijk} \leq 0 \qquad i \in HP, j \in CP \ , \ k \in ST$$
$$qcu_i - \Omega\, zcu_i \leq 0 \qquad i \in HP$$
$$qhu_j - \Omega\, zhu_j \leq 0 \qquad i \in CP$$
$$z_{ijk}, z_{cui}, zhu_j = 0{,}1$$

*Calculation of approach temperatures.*

$$\mathrm{d}t_{ijk} \leq t_{i,k} - t_{j,k} + \Gamma(1 - \mathrm{z}_{\mathrm{ijk}}) \qquad k \in ST, i \in HP, j \in CP$$
$$\mathrm{d}t_{ijk+1} \leq t_{i,k+1} - t_{j,k+1} + \Gamma(1 - \mathrm{z}_{\mathrm{ijk}}) \qquad k \in ST, i \in HP, j \in CP$$
$$\mathrm{d}tcu_i \leq t_{i,NOK+1} - TOUT_{CU} + \Gamma(1 - \mathrm{zcu}_{\mathrm{i}}) \qquad i \in HP$$
$$\mathrm{d}thu_i \leq TOUT_{HU} - t_{j,1} + \Gamma(1 - \mathrm{zhu}_{\mathrm{j}}) \qquad j \in CP$$

The temperature between the hot and cold streams at any point of any exchanger will be at least EMAT:

$$\mathrm{d}t_{ijk} \leq \mathbf{EMAT}$$

*Objective function.*

The objective function is to minimize utility cost and capital cost

$$\mathbf{Min} \ \sum_{i \in HP} CCU\, qcu_i + \sum_{j \in CP} CHU\, qhu_j + \sum_{i \in HP} \sum_{j \in CP} \sum_{k \in ST} CF_{ij}\, z_{ijk} + \sum_{i \in HP} CF_{i,CU}\, zcu_{ijk} + \sum_{j \in CP} CF_{j,HU}\, zhu_j$$

## 3. Results and Dicussion

For doing HEN retrofit, the stage model was firstly tunned at EMAT = 35 ºC .to generate the same HEN as the existing one consuming hot and cold utilities about 105.2 and 100.8 MW, respectively, as shown in Fig. 4.

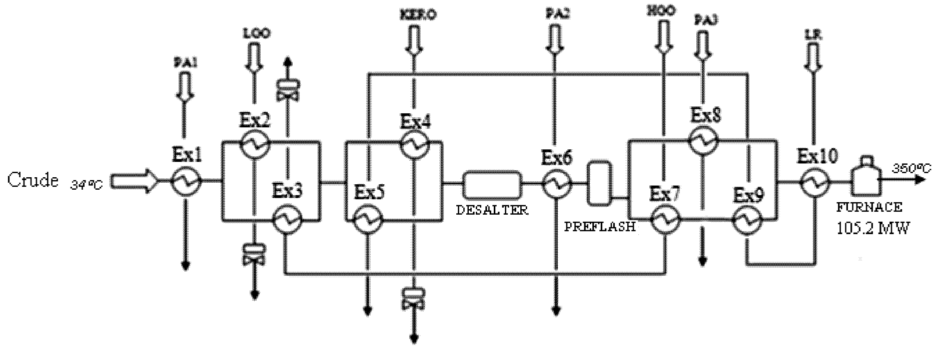

***Figure 4.*** *Existing HEN with EMAT = 35 ºC*

After that, the exchanger matching variables in the model were fixed at the same location as one of the base case. By reducing EMAT to 16 ºC , the model generated the HEN design with less hot and cold utilities of 103.8 MW and 98 MW, respectively.

This retrofit design needed three new exchangers, and three existing exchanger area to be modified as shown in Fig. 5.

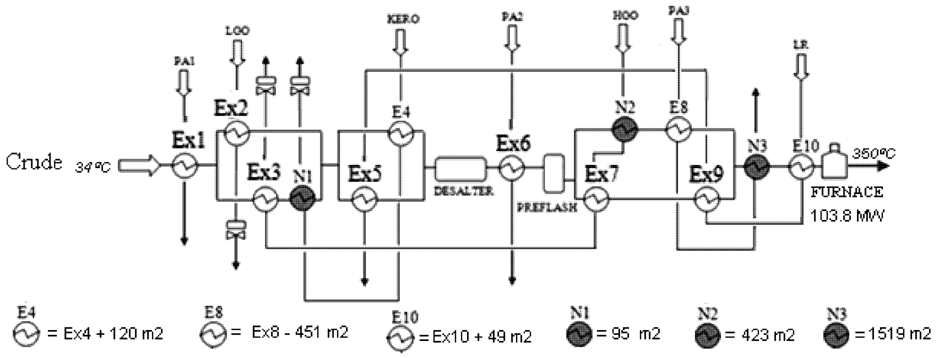

***Figure 5.*** *Retrofitted HEN with EMAT = 16 ºC*

Heat demand supply diagram of the existing HEN ,as shown in Fig. 6, was generated to show heat demand of crude (area under the curve) and increased crude temperature by heat supply from hot streams of pump-around, and product streams. It showed the furnace inlet temperature was 247 ºC. The diagram of retrofitted HEN was also shown in Fig. 6. It showed the furnace inlet temperature was raised to 250 ºC by this retrofitted HEN having more exchanger area of 1754 $m^2$ than the existing one. This HEN gained more heat recovery from hot streams; KERO, HGO, PA3, and LR to reduce the furnace duty about 1.3 %.

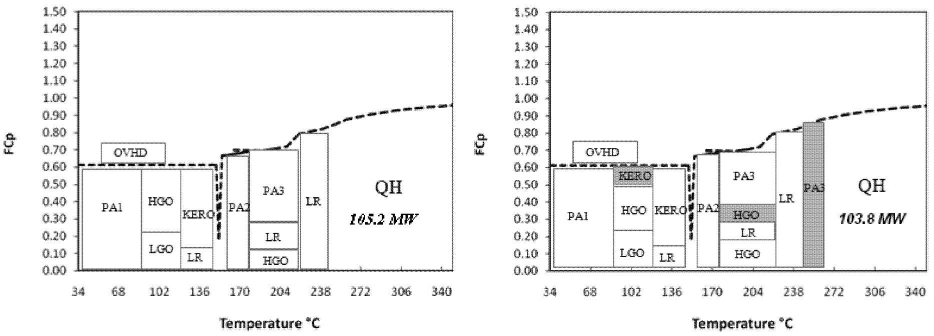

***Figure 6.*** *Heat demand –supply diagram of existing (left) and retrofit (right) networks*

## 5. Conclusions

The result showed that three new exchangers were added, and area of three existing exchangers were modified to recover heat from hot streams, KERO, HGO, PA3, and LR, to preheat crude and also increase the furnace inlet temperature, resulting in energy savings at furnace and coolers about 1.3% and 2.8%, respectively, as shown in Table 1.
The future work will be to develop the relocation constraint to do retrofit HEN and optimize the exchanger area by adding the equation of exchanger area to the objective function of the superstructure stage model.

**Table1.** The result of retrofit design

| Design | EMAT (°C) | Number of process exchanger | Utilities (MW) | | | |
|---|---|---|---|---|---|---|
| | | | QH | Saving (%) | QC | Saving (%) |
| **Base case** | 35 | 10 | 105.2 | 0 | 100.8 | 0 |
| **Retrofit design 1** | 16 | 13 | 103.8 | 1.3 | 98.0 | 2.8 |

## Nomenclature

HP = Set of Hot Process Streams
CP = Set of Cold Process Streams
ST = Set of Stage No.
TIN = inlet temperature of stream
$CCU$ = unit cost for cold utility
$\beta$ = exponent for area cost
$\Omega$ = upper bound for heat exchange
F = heat capacity flow rate
U = overall heat transfer coefficient
$CF$ = fixed charge for exchangers
TOUT= outlet temperature of stream
$CHU$ = unit cost of hot utility
$NOK$ = total number of stages
$\Gamma$ = upper bound for temperature difference
$dt_{ijk}$ = temperature approach for match ( $i,j$) at temperature location $k$
$dtcu_i$ = temperature approach for match of hot stream $i$ and cold utility
$dthu_j$ = temperature approach for match of cold stream $j$ and hot utility
$q_{ijk}$ = heat exchanged between hot process stream $i$ and cold process stream $j$ in stage $k$
$qcu_i$ = heat exchanged between hot stream $i$ and cold utility
$qhu_j$ = heat exchanged between hot stream and cold stream $j$
$t_{i,k}$ = temperature of hot stream $i$ at hot end of stage $k$
$t_{j,k}$ = temperature of cold stream $j$ at hot end of stage $k$
$z_{ijk}$ = binary variable to denote existence of match ($i,j$) in stage $k$
$z_{cui}$ = binary variable to denote that cold utility exchanges heat with stream $i$
$z_{huj}$ = binary variable to denote that hot utility exchanges heat with stream $j$

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