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Optimal Design of Heat Exchanger Network in Oil Refineries

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The performance of the heat exchanger network (HEN) in a plant is an important aspect of energy conservation. Pinch technology and mathematical programming techniques offer an effective and practical method for designing the HEN for new and retrofit projects. The fluid catalytic cracking (FCC) is a dominant process in oil refineries and there has been a sustained effort to improve the efficiency and yield of the unit over the years. HEN optimal design in FCC process is an essential element in reducing the cost and improving the process as a whole. The objective of this work is to introduce a systematic procedure for designing optimal and flexible FCC-HEN that incorporates variations in feed flowrates and specs, and on same time considers different schedules imposed on the process. First, a hierarchical approach consisting of a general optimization formulation that is accounting for the anticipated schedules and heat integration during the FCC-HEN design phase will be used in this project. Then, a new targeting approach will be introduced because of the complexity of the formulation for heat integration with varying flows and temperatures. Finally In order to synthesize a flexible configuration of the FCC-HEN, a multiperiod formulation will be developed and applied on FCC process to account for the variations associated with the anticipated operational schedules.

1. Introduction

Fluid catalytic cracking (FCC) is an important process in oil refineries. It converts atmospheric gas oil, vacuum gas oils, certain atmospheric residues and heavy stock recovered from other refinery operations into high-octane gasoline, light fuel oils and olefin rich light gases. Heat exchanger network (HEN) in FCC process can be optimized using pinch technology, mathematical programming, combination of both or stochastic methods. There are two ways for considering HEN design which are based on either sequential or simultaneous approaches. The sequential approaches are taking in consideration fixed supply and target temperatures while the simultaneous approaches are considering other design aspects simultaneously with the optimal design of HEN.

Over the past 30 years, significant research contributions have been made in developing design techniques for the synthesis of heat exchange networks (HENs) in general. Much of this work has focused on heat integration as the overarching goals with objectives

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such as minimizing heating and cooling utilities and total annualized cost of the network. On the other hand, much less work has been done in the area of reconciling heat integration with other process objectives. Mathematical programming techniques have been effectively used to address several important categories of HENs. In an attempt to exploit the interactions between the process operating conditions (i.e. stream temperatures and flowrates) and the heat recovery network, Papoulias and Grossmann (1983) developed a strategy for simultaneous optimization of the process and heat integration based on mixed integer linear programming (MILP). This approach allows the flowrates to vary as part of optimizing the process and the associated network of heat exchangers. In order to avoid nonlinear terms in the formulation, fixed temperature intervals are defined. Duran and Grossmann (1986) introduced a mathematical approach for the optimization of heat exchange networks where the supply and target temperatures are allowed to vary. Mathematical constraints are introduced to account for the unknown temperature and to locate candidate and true pinch points, thereby ensuring that the final flowsheet will feature the minimum utility target. According to this approach, bounds on the energy requirements of the process are explicitly included within the synthesis problem; however, the structure and overall cost of the heat recovery system are not traded off with process costs. Grossmann et al. (1998) developed another method for the simultaneous optimization of flowsheet and heat integration. It is based on introducing integer variables that give a general formulation for heat loads and composite curves. Yee et al. (1990) proposed a structural optimization model, where process alternatives are optimized simultaneously with the heat exchanger network that accommodates the heating and cooling requirements of the process streams. They introduced a superstructure representation which included many possible flowsheet alternatives. However, the number of variables and constraints that are needed to produce the required mathematical representations may be large. Thus, simplifying assumptions may be required.

2. Scope

Since the scope of this work is related to oil refineries, there are attempts designing HEN for various units in oil refinery. Some of these consider design or retrofitting for HEN in crude distillation or cracking units. Querzoli et al. (2003) reviewed the actual heat integration performance of the existing crude distillation unit (CDU) and residual cracking unit (RCU) of refining processes and identified potential areas for improvement. They developed retrofit designs and operating strategies to increase heat integration also determine the economics of the retrofit designs to assess if any of the options are commercially attractive. Fraser and Gillespie studied the energy integration on the whole oil refinery where they identified potential energy savings in the plant. It is mainly feasibility study rather than actual retrofitting of existing HEN of the oil refinery.

The contribution of Al-Riyami et al (2001), which is interestingly enough study on FCC-HEN. They used pinch analysis for the retrofit designs of FCC. The retrofit objective was to improve energy recovery and performance of the existing network. Al-Riyami used the incremental area efficiency method for targeting and the network pinch method for retrofit designs. The existing network had a ΔT_{min} of 24 °C and an area efficiency of 81 %. The incremental area efficiency method produced a target ΔT_{min} of 12 ºC.

Most of the work done on FCC-HEN design is based on fixed supply and target temperatures so that HEN is designed based on the most expected heating and cooling utilities requirement. For example, work by Al-Riyami et al. (2001) where FCC-HEN is retrofitted with fixed supply and target temperatures and flows. However, that misses the opportunity to design an optimal HEN that allows flexibility considering different variations in the process parameters as a result of increase in production or more stringent environmental regulations. In FCC process, heat integration is typically included in the base-case design according to the nominal input data.

3. FCC industrial unite (heat recovery)

Fluid Catalytic Cracking unit in oil refinery in Saudi Arabia is taken as a base case design for the study on efficient use of energy in oil refining industry. Figure 1 shows the HEN in the FCC plant where that covers energy use in the reactor-regenerator section and the fractionation section as well.

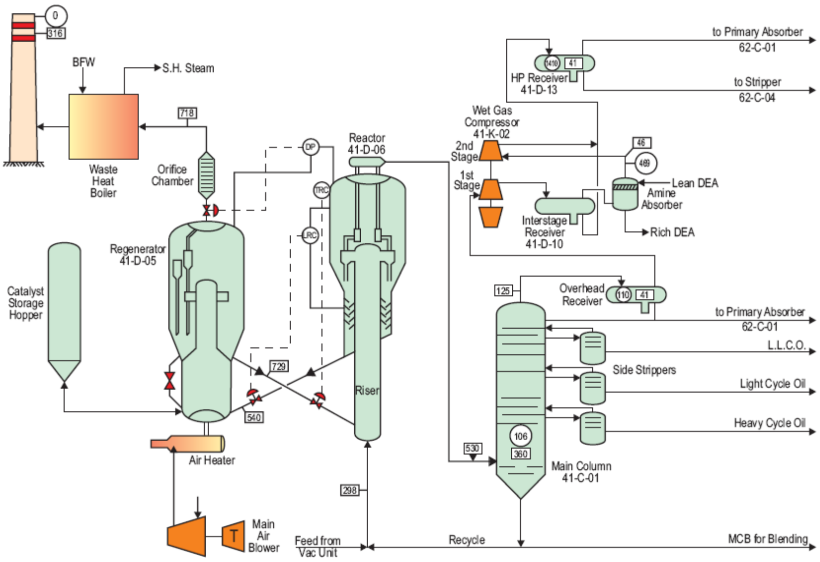

Figure 1: FCC industrial case in Saudi refinery

The heat exchangers in the FCC plant are divided into data are both Shell & Tube Heat Exchangers and Air Cooled Heat Exchangers. The Shell & Tube HE heats mainly the feed stream where the air cooled HE are mainly cooling the products. There are utility HEs as well as in process HEs. The streams and temperature data are extracted and shown in Table 1.

4. Analysis and Results

The analysis of HEs streams are shown in Table 1 where the HEs flows as well as the heat capacities of various streams are calculated by TBP curves using ASPEN simulation software. The properties of the light cycle oil, heavy cycle oil and other heavy products are calculated at the associated temperatures by the analysis using ASPEN.

The objective function of maximizing the gross profit of the FCC process is given by:

$$Maximize \quad Gross \quad Profit = \sum_t \sum_p C_{p,t}^{product} P_{p,t} - \sum_t POC_t - \sum_t \sum_z \left(C_{hot.t} HHU_z^{total} - C_{cold,t} HCU_z^{total} \right)$$

where $C_{p,t}^{product}$ is the unit selling price of product p during period t, POC_t represents the plant operating cost (e.g., feedstocks, utilities, etc.) during period t, $C_{hot.t}$ is the price of the heating utility and $C_{cold,t}$ is the price of cooling utility during period t. (Al-Mutairi and El-Halwagi, 2009).

Mathematical programming methods are used to optimize the production scheduling and maximizing the heat recovery from the FCC process. The problem is mixed integers programming where the branch and bound methods are used to solve it by the optimizer software.

Table 2 shows the results when the scheduling effects are considered for the FCC HEN design.

5. Conclusions

Simultaneous process scheduling and heat integration has been introduced and applied on FCC process. This approach includes design modifications, heat integration, and anticipated schedules. This approach determines the optimal production while considering heat integration of the process. Trade-off between the two competing objectives has been established in this approach. The results show the merits of including scheduling of production effects in the design phase of HEN in the oil refining industry

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Table 1: Shell & Tube Heat Exchangers

Heat Exchanger #	Fluid Name	Flow rate (kg/s)	in. Temp (°C).	out. Temp. (°C)	Fluid Name	Flow rate (kg/s)	in. Temp (°C).	out. Temp. (°C)
E - 04 (A-H)	Main Column Overhead	118.1	68	40.5	Cooling Water	214.1	33.3	50
E - 05 (A/B)	5 atm. Steam	4.9 K	137.8	170	Light Cycle Oil	140.7	219.8	190.6
E - 07	Stripped L..C.O	29.1	227.1	176.7	L.P Boliler Feed Water	38.4	138	160
E - 09	M.P Steam	44.9	192	192	H.C.O	50.5	336.6	218.3
E - 10	M.P Steam	13.95	192	192	Stripped H.C.O	17.9	323.2	218.3
E - 12 (A/B)	H.P. Steam	98.5	261	261	M.C Bottoms+Catalyst Fines	308.6	360	315.6
E - 13	Water	26.6	38.3	49	MCB Product+Catalyst Fines	4.44	260	138
E - 14 (A/B)	Vaccum Gas Oil	112.3	187.8	271.5	M.C.Bottoms+Catalyst Fines	212.2	360	315.6
E - 15	High Pressure Steam	25.45	261	261	M.C.Bottoms+Catalyst Fines	63.9	360	304.4
E - 16 (A/B)	M.P Steam	44.1	192	192	M.C Bottoms+Catalyst Fines	63.9	304.4	212.8
E - 17 (A/B)	Interstage Fluid	18.73	77	40.5C	Cooling Water	112.4	33.3	40.5
E - 18 (A-D)	High Pressure Fluid	118.8	73	40.5	Cooling Water	184	33.3	50
E - 19	20% wt Amine Soln.	70	60	46.1	Cooling Water	71.8	33.3	46.1
E - 20 (A/B)	M.P Steam	122.8	192	192	M.P.Bottoms+Catalyst Fines	308.6	315.6	260
E - 21	MCB Product	4.44	149	82	Water	26.6	33.3	38.3
E - 22	Cooling Water	4.14	33.3	49	Vaccum Gas Oil	20.4	204	149
E - 25 (A/B)	Light Cycle Oil	-	79.4	37.8	Cooling Water	-	30	41.1

Table 2: FCC-HEN base and optimum cases

Value	Base Case	Optimum Case
Feed (BPD)	27,000	45,000
Gasoline Pdn (BPD)	29,845	41,766
Q_H^{min} (MW)	9.1	7.6
Q_C^{min} (MW)	42.7	35.3
Gasoline Profit Annual ($MM)	12.5	18.6
Utilities Annual Cost ($MM)	2.2	1.88
Annual Profit ($MM)	8.4	15.2

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