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OPTIMIZATION OF HEAT EXCHANGER NETWORKS FOR A CRUDE DISTILLATION UNIT

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ABSTRACT

A common problem that occurs in crude oil refining, and other chemicals manufacturing industries is the following: The production process generates numerous streams of fluids, each stream at a certain temperature in ^{0}C known as its starting temperature. The temperature of each stream has to be changed to a different level known as its target temperature, for it to enter the next processing stage. If the target temperature of a stream is smaller than its starting temperature, then this stream has to shed some of the heat energy in it (i.e., it needs to be cooled) before entering the next processing stage; that's why such streams are known as hot streams. On the other hand, if the target temperature of a stream is greater than its starting temperature, then this stream needs to be heated before entering the next processing stage; that's why such streams are known as cold streams. This contribution provides a new methodology for optimizing crude oil distillation systems. The proposed approach determines the optimum operating conditions for the crude oil distillation unit, where the objective is maximum net profit, while proposing retrofit modifications for the heat exchanger network (HEN) that allow a feasible operation which gives a minimum utilities cost. To improve product profit, the yields of the most valuable products are increased, while considering product specifications, heat recovery and equipment constraints. An artificial neural network model (ANN) is generated to simulate the distillation unit, while the HEN model consists of a mass and energy balance formulated using principles of graph theory. The newness of this research lies in the simultaneous consideration of the distillation column and HEN models in the optimization algorithm, with the focus on profitability. Results show that an important economic improvements can be achieved.

Keywords: *Crude Distillation, Product, Optimization, Heat Exchanger Network, Neural Network*

INTRODUCTION

Distillation of crude oil is an energy demanding process central on petroleum refining. Ultimately, the distillation 'system' (the distillation unit and the associated heat exchanger network) may need to be adjusted to different operating situations, whether driven by economics reasons (e. g. increase of profits, reduction of operating costs) or technical reasons (e.g. changes in product specifications or feedstock conditions). The connection between the distillation unit and heat exchanger network is strong, the hot streams such as the condenser, distillation products streams and the pump-around are integrated with the cold streams, such as the reboilers and the crude oil feed. The remaining energy requirements are supplied by the fuel oil in the furnace and cooling water system. Several researches have considered the design of crude distillation systems in the past years, focuses on the design of crude oil distillation columns based on empirical and heuristics correlations [1]. In [2] and [3], it was proposed that sophisticated methods for revamps comprises the majority of crude oil distillation projects, retrofit design from both design decisions implemented in refineries were established and simplified using new computational tools. Adaptation of installed equipment to new operating situations such as increasing capacity and increasing energy efficiency compared to grassroots design projects are presented as a more economical alternative using retrofitting methodologies. However, optimization and the HEN can easily be used in a distillation unit, while retrofit is typically implemented only in the HEN. This study presents the optimization of crude oil distillation systems by new methodology. The proposed method considers the existing distillation column and HEN of a refinery distillation unit simultaneously, optimizing the operating conditions of the distillation system and recommending a revamp modifications for the HEN. The technique is applied in the optimization of existing crude oil distillation unit to reduce energy consumption and capital costs and also to increase product revenue.

Lately, research on the crude oil distillation systems optimization has received reasonable interested consideration. Complex distillation column has been simulated by developed simplified, statistical and rigorous models with each distillation model being implemented in optimization structures to determine the best arrangement (operating conditions and/or column structure) that achieves a certain objective function (e.g. decreasing operating costs, increasing product revenue, etc.).

Rigorous models to simulate and optimize crude oil distillation columns were employed by [4-6]. However, only the work of [5] considered the related HEN. The presented procedure to design the heat-integrated distillations system is given in a step-by-step in this study. The technique is based on procedures and involves strong user interaction. Though, rigorous models with good accuracy are difficult to implement these models in an optimization structure that considers both the HEN and column, due to the complex nonlinearities that need to be solved simultaneously.

Only [7] and [2] simplified models to overcome some of the limitations presented by rigorous models; these models are more robust and perform calculations in a lesser amount of time than rigorous models. These simplified models have been employed in systematic approaches to retrofit and design heat-integrated distillation systems that reflect the HEN structure. Though, the need to specify key components and their recoveries (rather than specifying product flow rates) is the major limitation of simplified models, as these models are based on the Fenske-Underwood-Gilliland method. An optimization methodology to determine key components and their recoveries based on the specification of flow rates and true boiling points of the distillation products and the solution of this optimization problem requires complex and iterative calculations, requiring sensible initial guesses to converge was developed by [2].

The works of [8] and [9] used statistical models to simulate and optimize the operating conditions of crude oil distillation columns. In the work of [9], they used real plant measurements to obtain an artificial neural network (ANN) model for the distillation column. The ANN model is applied in an optimization method to determine the operating conditions that produce improved product yields under the required quality conditions. However, since interactions with the HEN were not taken into account, the related HEN may not be able to accept the optimized operating conditions of the column. As an alternative, the distillation column and HEN to perform operational optimization was considered in the work of [8]. In their work, they considered regression models to simulate the crude oil distillation tower, and mass and energy balances to simulate the HEN and also rigorous simulations were performed to obtain the data to regress the distillation models. Their results shows that regression models are more robust and faster than rigorous models, and are suitable for implementation in a systematic optimization methodology.

Several methodologies have been proposed to optimize HENs. These approaches can be grouped into three categories: mathematical programming methods, pinch analysis methods and stochastic optimization techniques. As observed in [10],[7] and [2] that the stochastic optimization methods, particularly SA, have been successfully applied to retrofit HENs from crude oil distillation systems. Stochastic optimization methods have a good chance to find global optimum for non-linear problems with mixed integer and continuous variables, compared to mathematical programming and pinch analysis, due to the random nature of the optimization method. Thus, SA has been carefully chosen in this work as the optimization algorithm. Only the works of [7],[2] and [8] include the distillation column and HEN details simultaneously as mentioned earlier in the methodologies. Though, the approach developed by [8] is restricted to operational optimization, the methodologies proposed by [7] and [2] can be applied for grassroots design, operational optimization or retrofit. In this research, an ANN model is built to enable optimization of heat-integrated crude oil distillation units. The strategy given in this work considers the distillation unit and HEN concurrently to determine the distillation operating conditions that increase product revenue and decrease operating costs. The method proposes minimal HEN retrofit adjustments to accommodate the new operating conditions of the column.

DEVELOPMENT OF MODELS

Distillation column model

In this research, various rigorous simulations are performed in Aspen HYSYS and an ANN model built by regressing a set of samples that represent the column behavior is used to simulate the crude oil distillation column to obtain the regression. The inputs or independent variables of the distillation column are randomly varied through their lower and upper values to generate the results. In this case, the duties and temperature drops of the pump-around and the column inputs comprise the product flow rates. Variables that are used to evaluate the objective function and constraints are gathered from the simulation results. These variables are the outputs and are the 5 % and 95 % TBP points (T5 % and T95 %), to evaluate the required column diameters; product quality constraints, to avoid exceeding the installed column dimensions in the design; and finally, process stream data (i.e. heat capacity of streams requiring heating or cooling and temperatures), to simulate the HEN.

This large number of outputs needs three ANNs to create the new distillation column model. The first ANN is to determine the feasibility of the distillation inputs; that is, it rejects scenarios that do not converge using rigorous models. In this study, a value of 1 or 0 is assigned to each scenario, depending on whether the rigorous simulation has converged. This feasibility network is regressed against the generated vector of ones and zeros. The second calculates the column diameters for the different sections, and the T5 %, T95 % points of the column. The third ANN determines the process stream data: heat capacity flow rates of all process streams involved, such as reboilers, condenser, pump-around, product streams, supply and target temperatures, and etc. In the last two ANNs, only converged scenarios are used to regress these. All the ANNs employed to build the new distillation model are designed as feed-forward back-propagation networks [11]. The first ANN contains two layers that uses hyperbolic tangent sigmoid transfer functions. The second and third ANNs consist of two and three layers, respectively; and apply hyperbolic tangent sigmoid transfer functions for the hidden layers and linear transfer functions for the output layers. The ANN toolbox embedded in V8.5.0 of MATLAB® (The MATH WORKS Inc., USA) is used to perform the calculations.

Heat Exchanger Network Model

In this contribution, the model used to simulate the HEN is established on the method of [12]. The HEN model involves two linear systems that characterize the mass and energy balances, respectively, expressed using principles of graph theory. The model proposed by [12] has been improved in this contribution to identify the heat exchangers in terms of heat load instead of area and extended to simulate the HEN allowing temperature-dependent heat capacities.

Feasibility Solver

Assume a HEN structure, supply temperatures, flow rates of process streams, heat capacity, exchanger heat loads and stream split fractions, the HEN simulator calculates the utility needed and outlet temperatures of every heat exchange unit, splitter and mixer. Nevertheless, this calculated temperatures should not interrupt the stream energy balance or minimum temperature approach constraints. If any of these constraints is interrupted, a feasibility solver is called to compute new heat loads and split fractions that regain feasibility. The proposed feasibility solver as in (1) is extended to include the calculation of split fractions is based on the one developed by [2]. This feasibility solver is formulated as non-linear least square problem (NLLSQ):

$$\min_{Q,sf} \left\| f\left(Q, sf\right) \right\|_2^2 = \min_{Q,sf} \left[\sum_{i=1}^{N_{HX}} \min\left(A\right)^2 + \sum_{k=1}^{N_{ST}} \left(B\right)^2 \right] \quad (1)$$

Where

$$A = \left(TH_i^{out} - TC_i^{in} - \Delta T_{min}, TH_i^{in} - TC_i^{out} - \Delta T_{min}, 0\right)$$

and

$$B = \left(TT_{cal,k} - TT_k\right)$$

Q and *sf* are vectors representing the exchanger heat loads and split fractions, respectively; *TH* and *TC* are the temperatures for hot and cold stream at the inlets and outlets of heat exchanger; N_{HX} is the total number of heat exchange units; TT_{cal} and *TT* are the calculated and specified target temperatures of process stream *k*, respectively; N_{ST} is the total number of process streams. The NLLSQ problem is solved by the application of the trust-region-reflective algorithm embedded in MATLAB. The HEN design is rejected if the solver is unable to achieve network feasibility.

Retrofit Model

The HEN structural modifications is performed by employing the retrofit model of [10]. The retrofit options, referred to in this contribution as "HEN moves", comprise adding, deleting, re-piping, re-sequencing a heat exchanger; adding or deleting a splitter; modifying heat loads and changing stream split fractions. Practical constraints can be specified by the user, such as forbidden matches, maximum number of heaters or splitters per stream, etc. Once the fundamental modification is obtained, the new HEN is simulated. If the new design disrupts any HEN constraint, the feasibility solver is employed to redistribute heat loads and split fractions (where possible).

Simulation of the heat-integrated distillation system

The crude oil distillation column and the HEN constitute the heat-integrated distillation system. To accomplish the simulation of the distillation system, the crude oil distillation column is simulated first, established on its specified operating conditions. The simulation results of the distillation column gives the supply and target temperatures and deliver the heat flow capacity values of the supply and target temperatures, the assumption is that the heat flow capacity is a linear function of temperature. Subsequently, the input specifications for the HEN simulation are given by the supply and target temperatures and heat flow capacities of all process streams are calculated by the distillation model. For a given HEN structure, the HEN is simulated and the constraints are evaluated. To restore feasibility of the HEN design, the feasibility solver is employed when necessary.

Heat-Integrated Distillation System Optimization

The approach proposed in this contribution considers the optimization of the operating conditions and HEN structural modifications the distillation column and HEN simultaneously. This optimization problem involves continuous and integer variables, a MINLP (mixed integer non-linear programming) framework developed and solved using a simulated annealing, SA algorithm. The objective function is to maximize net profit, defined as:

$$NP = \sum_{j=1}^{N_{prod}} C_{prod,j} F_{prod,j} - \left(C_{crude} F_{crude} + C_{st} F_{st} + \sum_{k=1}^{N_{util}} C_{util,k} F_{util,k} + ACC \right) \quad (2)$$

where C and F are the unit prices and flow rates of distillation products (prod), crude oil (crude), stripping steam (st) and utilities (util); N_{prod} is the number of distillation products, N_{util} represents the total number of utilities; and ACC is the annualized capital cost of modifications to the HEN.

In the optimization, the distillation column inputs (distillation “moves”) and HEN “moves” are the degrees of freedom considered. Each move represents a change in an optimization variable. The SA algorithm selects the move to be implemented, subject to an assigned probability and a generated random number. The move probabilities help to increase the optimization procedure, providing a preference towards those variables that have the highest influence on the objective function. The values of the move probabilities are problem-specific; trials need to be done to establish appropriate values. Process constraints are used to guarantee that solutions are acceptable and practicable. For this purpose, T5% and T95% TBP points and column diameters are kept within acceptable limits during the optimization; column designs that doesn’t apply these constraints are rejected by the optimizer. For HEN retrofit, constraints comprise the maximum number of structural modifications, forbidden stream matches and maximum added heat transfer area per exchanger. The HEN feasibility solver includes energy balances and minimum temperature approach constraints. Equation (1) was solved by employing the SA algorithm by [2] and the MATLAB programming language was used for coding the heat-integrated distillation system model and the overall optimization framework.

RESULTS

Case study

Consider the crude oil distillation system in Warri Refining and Petrochemical Company (WRPC), Delta State, Nigeria consisting of a preheating train and a main distillation tower with three side strippers, three pump-around and one condenser. The atmospheric distillation column processes 120,000 bbl/day (0.221 m^3/s) of crude oil into five products: light naphtha (LN), heavy naphtha (HN), light distillate (LD), heavy distillate (HD) and residue (RES). The crude oil to be processed is the Escravos Light crude; steam is used as a stripping agent. An optimized design proposed by [2] were used for the stage distribution of the atmospheric column and initial operating conditions.

The HEN structure is illustrated in Figure 1. It consists of 22 heat exchange units (including the process furnace), with total used area of 5,302 m^2. The units 1 to 13 represent process-to-process heat exchangers; units 14 and 15 represent heaters; while units 17 to 24 are coolers. The minimum temperature approach is 25 °C. Hot and cold utilities are from fired heater and cooling water respectively. The current hot and cold utility requirements are 46.6 MW and 74.7 MW, respectively.
The product unit prices are based on the crude oil price of 2010 by [13] and calculated using the procedure proposed by [14]. Unit prices of stripping steam and utilities, and HEN modification costs are taken from [2]. A 2-year payback criterion with 5 % interest rate is assumed to calculate the ACC. The objective is to maximize the net profit defined in Eq (1) by increasing the yields of the most valuable products (in this case, LN and LD) while reducing operating and capital investment costs. To maintain product quality, T5% and T95% TBP points are constrained to vary less than 10 °C from their initial values. Column diameters are constrained to be less than or equal to the existing dimensions. A maximum of two new heat exchangers, two new splitters, one re-piping modification and one re-sequencing modification are allowed to be

implemented in the new HEN design. A total of 3,000 scenarios were simulated in Aspen HYSYS (of which 70 % converged). These simulation results were used to create the distillation column model. Figure 2 compares the ANN distillation model predictions against rigorous simulation results, showing good agreement.

The simulated annealing algorithm starts by evaluating the objective function of the base case. Then, random moves are performed to generate design alternatives according to the assigned probabilities. Table summarizes the optimization results for the distillation system. Figure 1 shows the original HEN and the proposed modifications to the HEN structure. The total used area of the optimized HEN is 5,349 m^2, of which 120 m^2 are from additional area for existing heat exchangers, and 74 m^2 from the new heat exchange unit.

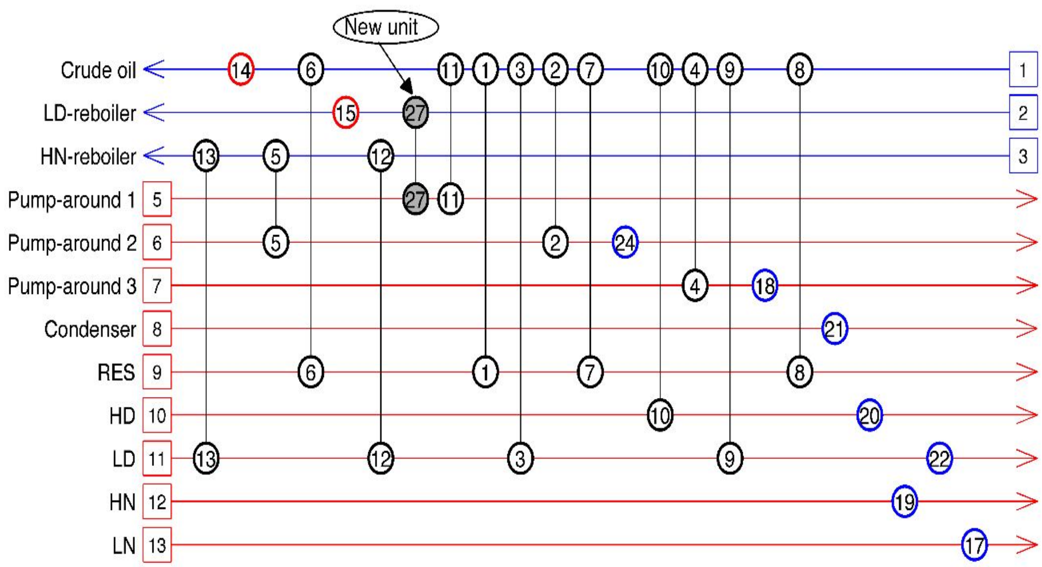

Figure 1: Initial heat exchanger network structure and proposed retrofit modifications.

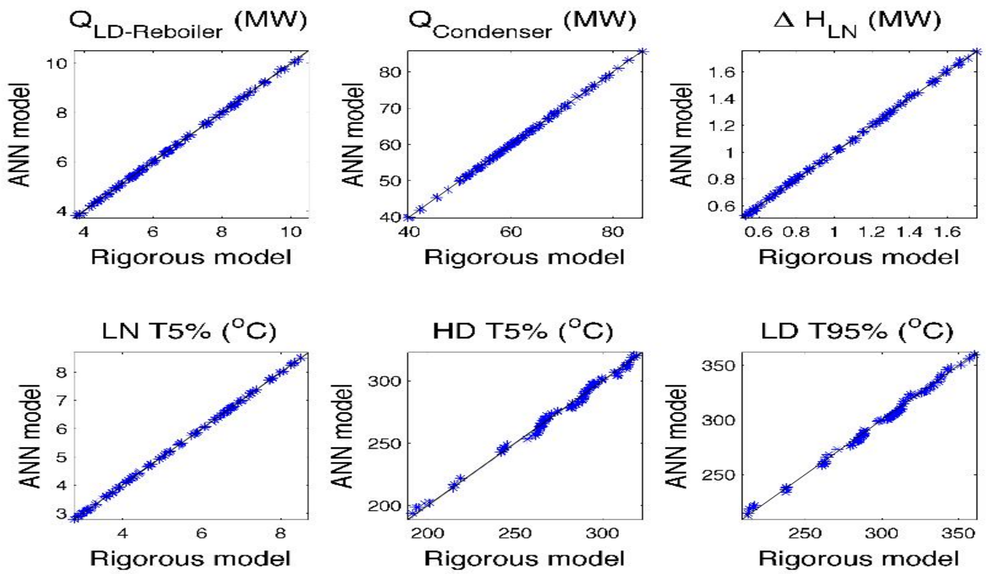

Figure 2: ANN distillation model test results. First row, duties of reboiler and condenser, and enthalpy change of LN product. Second row, T5% and T95% TBP points for some products.

Table I. SUMMARY OF OPTIMIZATION RESULTS FOR THE CRUDE OIL DISTILLATION SYSTEM

Item	Units	Base case	Optimized case	Change
Hot utility	(MW)	46.6	42.4	-4.2
Cold utility	(MW)	74.7	71.5	-3.2
Utility costs	(MM$/y)	7.3	6.7	-0.6
Steam cost	(MM$/y)	1.7	1.7	-
Crude oil cost	(MM$/y)	2,866.9	2,866.9	-
Operating cost	(MM$/y)	2,876.0	2,875.4	-0.6
Additional area	(m^2)	0	193.8	-
Annual capital cost	(MM$/y)	0	0.05	-
Product income	(MM$/y)	2,879.2	2,897.6	+18.4
Net profit	(MM$/y)	3.2	22.2	+19.0

MM$ denotes millions of US dollars

Net profit increases by about 19 MM$/y above the profit of the initial operating conditions and HEN structure. From Table , it can be seen that product revenue and crude oil costs dominate the distillation system economics in this case study. Annual capital investment to perform HEN retrofit modifications (0.05 MM$/y), plus the cost of steam and utilities

(8.4 MM$/y), are relatively small compared to product revenue (2,897.6 MM$/y) and crude oil costs (2,866.9 MM$/y).

From these results, it is demonstrated that changing the yields of the distillation products according to their value achieves considerable economic benefits, recovering the cost of revamping the HEN. The proposed optimization methodology is able to find design options that improve distillation system economics.

CONCLUSIONS

A new optimization approach for heat-integrated distillation systems has been developed in this work to increase product revenue and reduce operating costs. The flow rates of the most valuable products were optimized according to their commercial importance, while duties and temperature drops of the pump-arounds were selected to reduce the cost of fired heating and cooling water. The optimization algorithm proposed minimal topology modifications to the HEN to accommodate the new operating conditions of the column and to reduce energy requirements. T5% and T95% product specifications constraints were used to maintain product quality, while distillation column diameters and minimum temperature approach constraints were considered to guarantee feasibility of the system. An ANN model was used to simulate the crude oil distillation column, showing good agreement with results from rigorous distillation models. Furthermore, the ANN model demonstrated to be robust and suitable for implementation in the optimization strategy proposed in this paper. The HEN model employed in this work performs retrofit modifications taking into account practical constraints specified by the designer. Finally, the case study showed that the proposed strategy produced a design with improved net profit, requiring a relatively small investment to revamp the HEN.

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