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Retrofit of Heat Exchanger Networks for Optimising Crude Oil Distillation Operation

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The present work provides a new methodology for optimising 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. 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 novelty of this work lies in the simultaneous consideration of the distillation column and HEN models in the optimisation algorithm, with the focus on profitability. Results show that significant economic improvements can be achieved.

1. Introduction

Crude oil distillation is an energy intensive process that is central to petroleum refining. Over time, the distillation unit and the associated heat exchanger network – the distillation 'system' – may need to be adjusted to different operating scenarios, whether driven by technical reasons (e. g. changes in feedstock conditions or product specifications) or economics (e. g. reduction of operating costs, increase of profits).

There are strong interactions between the distillation unit and the heat exchanger network. The hot streams such as the pump-arounds, condenser and distillation products streams are integrated with the cold streams, such as the crude oil feed and reboilers. The remaining energy requirements are supplied by fuel oil in the furnace and cooling water.

In the past years, numerous publications have considered the design of crude distillation systems. Early works (Watkins, 1979) focus on grassroots design of crude oil distillation columns based on heuristics and empirical correlations. Later, new computational tools facilitated the development of more sophisticated methods for grassroots or retrofit design (Chen, 2008). From both design options, revamps constitute the majority of crude oil distillation projects implemented in refineries (Liebmann and Dhole, 1995). Retrofit methodologies are introduced as a more economical option for adapting installed equipment to new operating scenarios (e. g. increasing capacity, increasing energy efficiency), compared to grassroots design projects. While operational optimisation can be applied relatively easily in both the distillation unit and the HEN, retrofit is typically implemented only in the HEN.

This paper presents a new methodology for optimising crude oil distillation systems. The proposed approach considers the existing distillation column and HEN simultaneously; optimising the operating conditions of the distillation system and proposing revamp modifications for the HEN. The approach is applied in the optimisation of existing refinery distillation systems to increase product revenue and to reduce energy consumption and capital costs.

2. Previous work

Recently, the optimisation of crude oil distillation systems has received considerable research interest. Rigorous, simplified and statistical models have been developed to simulate the complex distillation column.

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Each distillation model has been implemented in optimisation schemes to determine the best configuration (operating conditions and/or column structure) that achieves a certain objective function (e.g. increasing product revenue, decreasing operating costs, etc.).

Rigorous models have been employed to simulate and optimise crude oil distillation columns. The work presented by Bagajewicz and Ji (2001) considered the distillation column and the associated HEN. In this work, a step-by-step procedure to design the heat-integrated distillations system was presented. The approach is based on guidelines and requires strong user interaction. Despite the good accuracy of rigorous models, it is difficult to implement these models into an optimisation framework that considers both the column and HEN, due to the large number of non-linear equations that need to be solved simultaneously.

Simplified models overcome some of the limitations presented by rigorous models; they are more robust and perform calculations in less time than rigorous models. Simplified models have been implemented in systematic approaches to design and retrofit heat-integrated distillation systems that consider the HEN structure (Chen, 2008). However, the main limitation of simplified models is the need to specify key components and their recoveries (rather than specifying product flow rates), since the model is based on the Fenske-Underwood-Gilliland method. Chen (2008) developed an optimisation methodology to determine key components and their recoveries based on the specification of flow rates and true boiling points of the distillation products. The solution of this optimisation problem requires complex and iterative calculations, requiring sensible initial guesses to converge.

Liau et al. (2004) have provided an expert system and López et al. (2012) used Mathematical Programming and developed statistical models to simulate and optimise the operating conditions of crude oil distillation columns. Liau et al. (2004) used real plant measurements to obtain an artificial neural network model for the distillation column. The ANN model is implemented in an optimisation technique to determine the operating conditions that produce improved product yields under the required quality specifications. Nevertheless, since interactions with the HEN were not taken into account, the associated HEN may not be able to accommodate the optimised operating conditions of the column. On the other hand, the work of López et al. (2012) considered the distillation column and HEN to perform operational optimisation. In their work, they used regressed models to simulate the crude oil distillation tower, and mass and energy balances to simulate the HEN. Rigorous simulations were performed to obtain the data to regress the distillation models. The resulting models are reported to be more robust and faster than rigorous models (López et al., 2012), and are suitable for implementation in a systematic optimisation methodology.

Numerous methodologies have been developed to optimise HENs. These approaches can be grouped into three categories: pinch analysis methods, mathematical programming methods and stochastic optimisation methods. Stochastic optimisation methods, particularly SA, have been successfully applied to retrofit HENs from crude oil distillation systems (Chen, 2008) providing the full details in the PhD thesis and (Smith et al., 2010) providing the resulting journal article from the thesis. Stochastic methods have a good chance to find global optimum for non-linear problems with mixed integer and continuous variables, compared to pinch analysis and mathematical programming, due to the random nature of the optimisation method. Hence, SA is selected in this work as the optimisation algorithm.

From the methodologies mentioned before, only the work of Chen (2008) and López et al. (2012) include the distillation column and HEN details simultaneously. While the approach developed by López et al. (2012) is restricted to operational optimisation, the methodologies proposed by Chen (2008) can be applied for grassroots design, retrofit or operational optimisation.

In this paper, an ANN model is built to facilitate optimisation of heat-integrated crude oil distillation systems. The strategy presented in this work considers the distillation unit and HEN simultaneously to determine the distillation operating conditions that improve product revenue and decrease operating costs. The approach proposes minimal HEN retrofit modifications to accommodate the new operating conditions of the column.

3. Distillation column model

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

The large number of outputs requires three ANNs to create the new distillation column model. The first ANN determines the feasibility of the distillation inputs; that is, it discards scenarios that do not converge using rigorous models. For this purpose, a value of 1 or 0 is allocated 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 ANN calculates the T5 %, T95 % points, and the column diameters for the different sections of the column. The third ANN determines the process stream data: supply and target temperatures, and heat capacity flow rates of all process streams involved, such as reboilers, condenser, pump-arounds, product streams, etc. Only converged scenarios are used to regress these last two ANNs.

All ANNs used to build the new distillation model are structured as feed-forward backpropagation networks (Beale et al., 2011). The first ANN contains two layers that employ hyperbolic tangent sigmoid transfer functions. The second and third ANNs consist of two and three layers, respectively; and use hyperbolic tangent sigmoid transfer functions for the hidden layers and linear transfer functions for the output layers. The ANN toolbox embedded in MATLAB (The MATH WORKS Inc.) is employed to perform the calculations.

4. Heat exchanger network model.

In this work, the model used to simulate the HEN is based on the approach proposed by De Oliveira Filho et al. (2007). The HEN model consists of two linear systems that represent the mass and energy balances, respectively, formulated using principles of graph theory. The model proposed by De Oliveira Filho et al. (2007) has been modified in this work to specify the heat exchangers in terms of heat load instead of area and extended to simulate the HEN considering temperature-dependent heat capacities.

4.1 Feasibility solver

Given a HEN structure, supply temperatures, heat capacity flow rates of process streams, exchanger heat loads and stream split fractions, the HEN simulator calculates the utility requirements and outlet temperatures of every heat exchange unit, splitter and mixer. However, the calculated temperatures should not violate the stream energy balance or minimum temperature approach constraints. If any of these constraints is violated, a feasibility solver is called to compute new heat loads and split fractions that regain feasibility. The proposed feasibility solver is based on the one developed by Chen (2008) and extended to include the calculation of split fractions. The feasibility solver is formulated as non-linear least square problem (NLLSQ) in Eq(1):

$$\min_{Q,sf} \left\| f(Q,sf) \right\|_2^2 = \min_{Q,sf} \left[\sum_{i=1}^{N_{HX}} \min\left(TH_i^{out} - TC_i^{in} - \Delta T_{min}, TH_i^{in} - TC_i^{out} - \Delta T_{min}, 0\right)^2 + \sum_{k=1}^{N_{ST}} \left(TT_{cal,k} - TT_k\right)^2 \right] \quad (1)$$

where Q and sf are vectors that represent the exchanger heat loads and split fractions, respectively; TH and TC are the hot and cold stream temperatures for inlets and outlets of heat exchanger i; 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 using the trust-region-reflective algorithm embedded in MATLAB. The HEN design is rejected if the solver is unable to achieve network feasibility.

4.2 Retrofit model

The retrofit model presented by Smith et al. (2010) is employed to perform HEN structural modifications. The retrofit options, referred to in this work as “HEN moves”, comprise adding, deleting, repiping, resequencing a heat exchanger; adding or deleting a splitter; modifying heat loads and changing stream split fractions. The user can specify practical constraints, such as forbidden matches, maximum number of heaters or splitters per stream, etc. Once a structural modification is proposed, the new HEN is simulated. If the new design violates any HEN constraint, the feasibility solver is employed to redistribute heat loads and split fractions (where possible).

5. Simulation of the heat-integrated distillation system

The heat-integrated distillation system comprises the crude oil distillation column and the HEN. To perform the simulation of the distillation system, the crude oil distillation column is simulated first, based on its specified operating conditions. The simulation results of the distillation column fix the supply and target temperatures and provide the heat flow capacity values at the supply and target temperatures. For simplicity, it is assumed that the heat flow capacity is a linear function of temperature. Next, the supply and target temperatures and heat flow capacities of all process streams calculated by the distillation model are used as input specifications for the HEN simulation. Given a HEN structure, the HEN is simulated and the HEN constraints are evaluated. The feasibility solver is employed when necessary to restore feasibility of the HEN design.

6. Heat-integrated distillation system optimisation

The methodology proposed in this work considers the distillation column and HEN together and optimises their operating conditions and HEN structural modifications simultaneously. As the optimisation problem involves continuous and integer variables, a MINLP (mixed integer non-linear programming) framework is developed and solved using a SA algorithm. The objective function is to maximise net profit, defined as:

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

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 annualised capital cost of modifications to the HEN.

The degrees of freedom considered in the optimisation are the distillation column inputs (distillation "moves") and HEN "moves". Each move corresponds to a change in an optimisation variable. The SA algorithm selects the move to be performed, depending on an assigned probability and a generated random number. The move probabilities help to improve the optimisation procedure, providing a bias towards those variables that have the greatest influence on the objective function. The values of the move probabilities are problem-specific; trials need to be carried out to determine appropriate values.

Process constraints are employed to guarantee that solutions are acceptable and practicable. In this case, T5 % and T95 % TBP points and column diameters are maintained within acceptable limits during the optimisation; column designs that violate these constraints are rejected by the optimiser. For HEN retrofit, constraints include the maximum number of structural modifications, forbidden stream matches and maximum additional heat transfer area per exchanger. Energy balances and minimum temperature approach constraints are included in the HEN feasibility solver.

The SA algorithm employed by Chen (2008) is used to solve Eq(2). The heat-integrated distillation system model and the overall optimisation framework are coded in MATLAB programming language.

7. Case study

Consider a crude oil distillation system consisting of a preheat train and a main distillation tower with three side strippers, three pump-arounds and one condenser. The atmospheric distillation column processes 100,000 bbl/day (0.184 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 Venezuela Tia Juana Light crude (Watkins, 1979). Steam is used as a stripping agent. The stage distribution of the atmospheric column and initial operating conditions are taken from an optimised design proposed by Chen (2008, Chap. 6.2).

The structure of the existing HEN is illustrated in Figure 1. The HEN consists of 22 heat exchange units (including the process furnace), with total used area of 5,302 m^2. Units 1 to 13 represent process-to-process heat exchangers; units 14 and 15 represent heaters; and units 17 to 24 are coolers. Minimum temperature approach is 25 °C. Fired heating and cooling water are used as hot and cold utilities. The current hot and cold utility requirements are 46.6 MW and 74.7 MW.

The product unit prices are based on the crude oil price of 2010 (EIA, 2012) and calculated using the procedure proposed by Maples (2000). Unit prices of stripping steam and utilities, and HEN modification costs are taken from Chen (2008, Chap. 6.2). A 2-year payback criterion with 5 % interest rate is assumed to calculate the ACC.

The objective is to maximise the net profit defined in Eq(2) 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 repiping modification and one resequencing 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 1 summarises the optimisation 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 optimised HEN is 5,349 m^2, of which

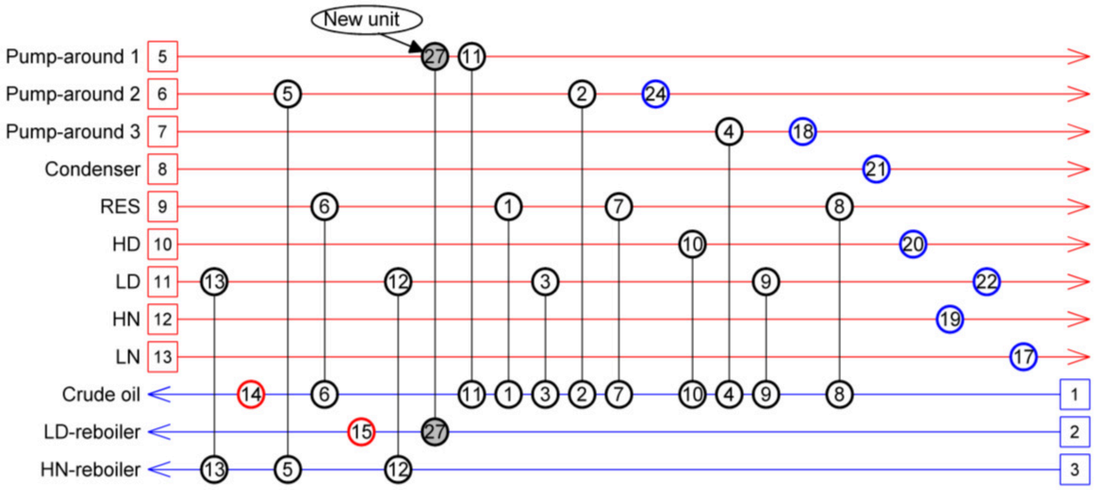

Figure 1: Initial heat exchanger network structure and proposed retrofit modifications.

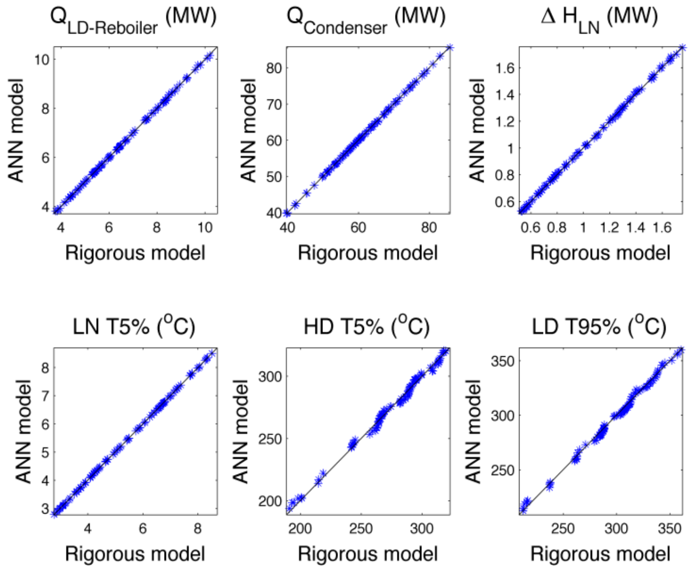

Figure 2: ANN distillation model test results. First row, duties of reboiler and condenser, and enthalpy change of LN product. Second row, T5% and T95% TBP points for some products.

Table 1: Summary of optimisation results for the crude oil distillation system

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

M$ denotes millions of US dollars

120 m^2 are from additional area for existing heat exchangers, and 74 m^2 from the new heat exchange unit.

Net profit increases by about 19 M$/y above the profit of the initial operating conditions and HEN structure. From Table 1, it can be seen that product revenue and crude oil costs dominate the distillation system economics in this case study. Annual capital investment to perform HEN retrofit modifications (0.05 M$/y), plus the cost of steam and utilities (8.4 M$/y), are relatively small compared to product revenue (2,897.6 M$/y) and crude oil costs (2,866.9 M$/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 optimisation methodology is able to find design options that improve distillation system economics.

8. Conclusions

A new optimisation approach for heat-integrated distillation systems has been developed in this work. The main contributions of this approach consisted of 1) the column and HEN being optimised together, allowing interactions to be exploited more than for approaches with decoupled column and HEN; and 2) the use an ANN crude oil distillation model regressed using rigorous model simulations.

To increase product revenue and reduce operating costs, the flow rates of the most valuable products were optimised 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 optimisation 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 optimisation strategy proposed in this paper. The time and effort required to obtain the distillation samples and regress the ANN model was compensated by its simplistic equations: neither initial guesses nor multiple iterations were necessary to simulate the column with this new simplified model.

The HEN model employed in this work performs retrofit modifications taking into account practical constraints specified by the designer and temperature-dependent stream properties, such as heat capacity flow rate. The capability of incorporating user-defined topology constraints allows more realistic designs to be achieved as issues, such as plant layout restrictions, can be addressed. 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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