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A New Optimisation-based Design Methodology for Energy-efficient Crude Oil Distillation Systems with Preflash Units

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In a heat-integrated crude oil distillation system with an atmospheric distillation unit and heat recovery system, pre-separation units (a preflash or prefractionator) can help to reduce the furnace duty and improve energy efficiency of the system. The high operating and equipment cost and complexity of the system motivate the development of systematic approaches for optimal design. The approach needs to consider both design of the distillation unit and the optimisation of operating conditions in the system, including those related to the preflash unit. This work introduces an optimisation-based methodology for the design of crude oil distillation systems with preflash units. The objective is to minimise fired heat demand of the system while meeting product quality and yield specifications, where pinch analysis is applied to estimate minimum utility requirements. A stochastic optimisation algorithm (a genetic algorithm) is applied to identify the feed location of the flash vapour, the number of stages in each column section and the optimal operating conditions. Operational optimisation variables include pump-around duties and temperature drops, stripping steam flow rates, the column feed temperature, reflux ratio and preflash temperature. The approach is based on the simulation–optimisation technique of Caballero et al. (2005). In order to facilitate integration of modelling and optimisation, an interface between MatLab R2016a and Aspen HYSYS v8.8 is employed. A case study illustrates how the design methodology proposed in this work can reduce demand for fired heating.

1. Introduction

A crude oil distillation system, such as that shown in Figure 1, comprises crude oil distillation units with side strippers and pump-arounds, a preheat train and, optionally, pre-separation units, such as flash units and prefractionation columns. These systems are complex, highly integrated and energy-intensive, and therefore benefit from systematic approaches for design optimisation. All crude oil fed to every petroleum refinery is processed in the crude oil distillation system; therefore it is imperative that this large-scale, energy-intensive process is designed for optimal operation. In particular, methodologies are needed to design optimised processes that maximise heat recovery and separation performance and minimise fuel consumed in furnaces for both economic and environmental benefit.
This work presents a systematic approach for the design of a cost-effective, energy-efficient heat-integrated crude oil distillation system with a preflash unit. Preflash units allow some material to bypass the furnace upstream of the atmospheric distillation unit (ADU), reducing fuel consumption, and achieve some preliminary separation of light components, reducing the separation load of the main column. The location to which the preflash vapour is fed to the main column is a degree of freedom that can help to improve the energy efficiency of the system (Ji and Bagajewicz, 2002). The methodology applies rigorous simulation models and stochastic optimisation techniques to select flash and column operating conditions and the column and flowsheet structure, while meeting constraints related to product quality and yield.

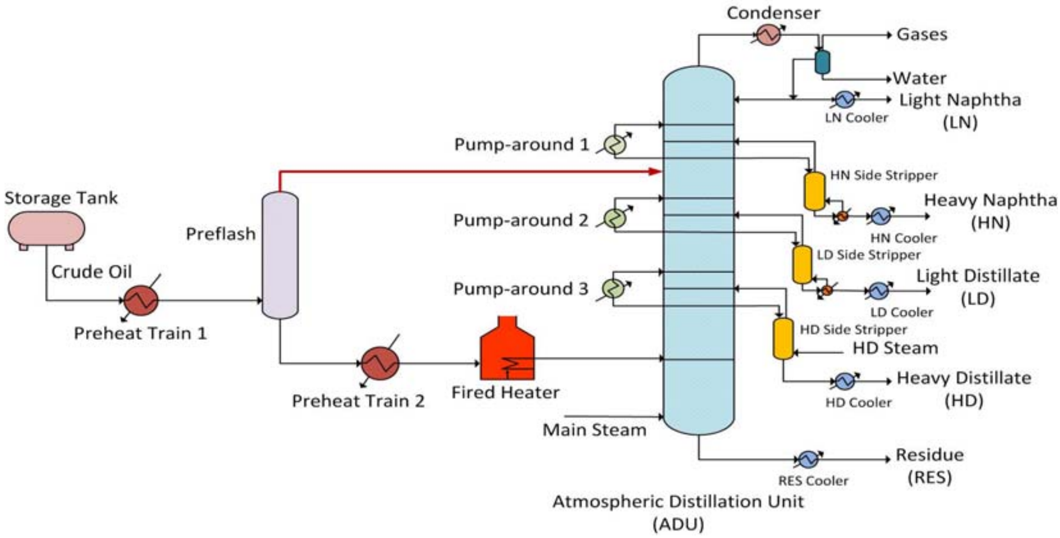

Figure 1: Crude oil distillation system with a preflash unit

2. Methodology

The aim of this work is to develop a methodology for the design of energy-efficient atmospheric crude oil distillation systems that include a preflash unit, accounting for product quality, product yield and heat integration. The approach addresses design of the atmospheric distillation unit and selection of preflash conditions, following the approaches of Ibrahim et al. (2017) and Caballero et al. (2005), where a MatLab–HYSYS interface is employed to facilitate the simulation and optimisation of the system.

The crude oil distillation unit is modelled in Aspen HYSYS v8.8, applying the '3ss crude' column template for this purpose; this software has been employed in industrial practice because of its ability to generate accurate simulation results. The Aspen HYSYS simulation model represents the flowsheet structure and the column design (number of stages in each section and location of feed and draw stages and locations of pump-arounds, stripping steam feeds and side-stripper reboilers). This flowsheet includes a preflash unit, where the destination of the preflash vapour is a design degree of freedom. Therefore, the flash vapour is fed to a stream splitter with n outlets, each of which is connected to a different location in the main column. The stream splitter is specified to send 100 % of the inlet stream to only one outlet stream; in this way, the flowsheet configuration can be varied using the stream splitter specifications.

The design of the column sections is addressed by including redundant stages in each section and defining the Murphree stage efficiency for each stage in each section of the column to be zero or one. In this way, existing trays can be activated (by setting the stage efficiency to 1), to allow mass transfer, or deactivated (by setting the stage efficiency to 0), to disallow mass transfer (Ibrahim et al., 2017). As a result, the number of active stages in each section and therefore the total number of stages in the column can be altered easily, by changing a process variable, without needing to explicitly change the column structure.

The model also represents process operating conditions. Within the flowsheet, the heating of the crude oil from ambient conditions to the furnace inlet temperature is modelled using one heater upstream of the flash unit and one heater representing a second preheat train upstream of the furnace. The outlet temperature of the upstream heater, i.e. the preflash temperature, is an important degree of freedom in the flowsheet design. Other design variables to be selected include column operating conditions, namely pump-around duties and temperature drops, stripping steam flow rates, column feed temperature, preflash temperature and reflux ratio. In the simulation model in Aspen HYSYS, product quality may be specified in terms of product boiling ranges (e.g. T5 % and T95 %, the boiling temperature when 5 % and 95 % of the material, respectively, has vaporised using a standard test, such as ASTM D86). Independent variables are then manipulated by the simulation algorithm to attempt to meet these specifications and converge the simulation.

Pinch analysis is applied to evaluate the minimum utility demand of the system, assuming heat recovery within the crude oil distillation system is maximised. The grand composite curve (GCC) is generated for each simulated design – using results of the simulation relating to stream inlet and outlet temperatures and heating and cooling duties; the minimum approach temperature is specified by the user. The grand composite curve is then used to evaluate the minimum demand for fired heating, which is an important performance indicator. Detailed heat exchanger design is not directly addressed (Ledezma-Martínez et al., 2018).

The above model can be used repeatedly, with trial and error or systematic searches, to search for designs that perform well in terms of the performance indicator. Instead, following Caballero et al. (2005) and Ibrahim et al. (2017), the search is automated: an interface is created between MatLab R2016a and Aspen HYSYS v8.8 which permits MatLab to read from and write to Aspen HYSYS (AspenTech, 2010). A MatLab subroutine (Morandin, 2014) uses the results of each converged simulation to apply pinch analysis and to generate a grand composite curve for the process, from which the minimum hot and cold utility demand is calculated.
The automation interface is embedded within the optimisation framework summarised in Figure 2. The optimisation algorithm selects values of process variables, including those determining the flowsheet or column structure, simulates the corresponding flowsheet, evaluates it and then selects a new set of inputs. A genetic algorithm is selected as the optimisation technique because it is known to be effective in finding good solutions to complex process design problems involving both continuous and discrete design choices (Kotecha et al., 2010). It is also simple to implement a genetic algorithm, using MatLab R2016a Global Optimization Toolbox. The optimisation parameters for the genetic algorithm are: population size, number of generations, and termination criteria. In this work, the optimisation terminates after a given number of generations or if the objective function does not improve by more than a certain tolerance over a given number of generations. Relevant optimisation constraints include the upper and lower limits of optimisation variables and constraints on integer variables (e.g. only one stream from the flash vapour has a non-zero flow rate; the maximum and minimum number of stages is specified for each column section). If an Aspen HYSYS simulation does not converge within a given number of iterations, a penalty term (a scalar of the same magnitude as the objective function) is applied to the objective function.
Typically, in the process simulation model, there are fewer degrees of freedom than there are specifications, so some important specifications are expressed as constraints in the optimisation problem. In line with industrial practice and the flexibility of downstream units, product quality constraints related to boiling range (ASTM D86 T5 % and T95 %) may be set with a wide tolerance (±10 °C). In addition, even though product quality specifications are imposed, it is possible for these to be met but the yield of products to decrease (i.e. more of the column feed is relegated to the Residue stream, for further processing in a vacuum tower, and flow rates of more valuable product streams may decrease). Therefore the flow rate of the Residue stream is constrained to be no more than that in the base case design (Ledezma-Martínez et al., 2018). If the product quality or residue flow rate constraints are violated, a penalty term – a scalar multiplied by amount by which the constraint is exceeded – is added to the objective function.

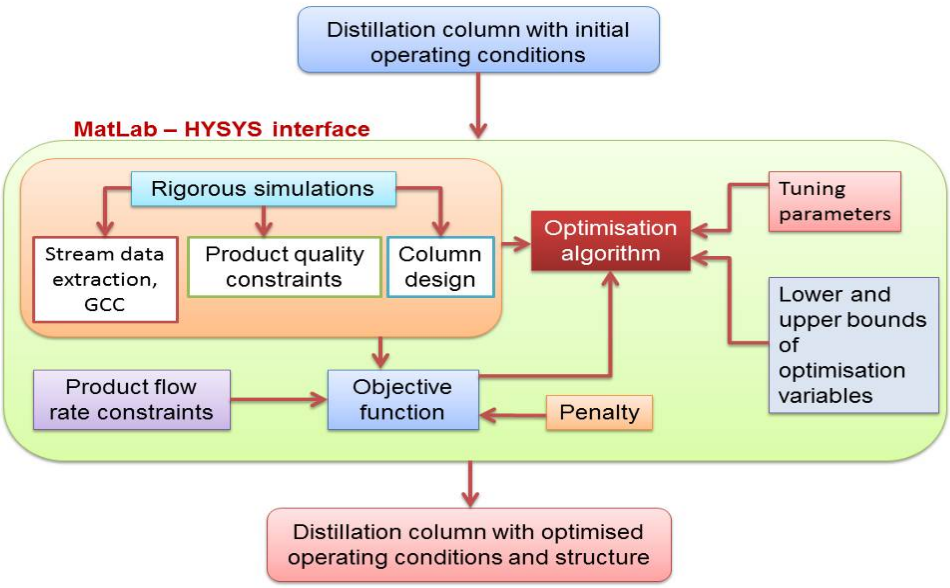

Figure 2: Simulation-optimisation framework

3. Case Study

The case study is based on data reported by Watkins (1979) and the base case is an unoptimised design presented by Chen (2008). The crude oil distillation system shown in Figure 3 comprises a preflash unit and an atmospheric distillation unit with a condenser, three pump-arounds and three side strippers (where the HN and LD strippers use reboilers, rather than live steam). The crude oil distillation unit produces five products: Light Naphtha (LN), Heavy Naphtha (HN), Light Distillate (LD), Heavy Distillate (HD) and Residue (RES). The system processes 100,000 bbl d^{-1} (660 $m^3 h^{-1}$) of Venezuelan Tia Juana light crude oil. Product specifications are expressed in terms of ASTM D86 T5 % and T95 %. The oil characterization tool in Aspen HYSYS v8.8 is used to cut the oil into 6 real components and 25 pseudocomponents. Vapour leaving the preflash unit is sent to one of five different locations in the main column (one per section). To provide a reasonable basis for comparison, the base case is first optimised without a preflash unit, then the base case design is optimised with a preflash unit (but without making any changes to column design); finally, the column design is optimised.

The optimisation problem has 11 operating variables (3 pump-around duties, 3 temperature drops, 2 stripping steam flow rates, column feed temperature, preflash temperature and reflux ratio). The feed location in the main column of the flash vapour and the column structure (number of trays in each of 8 sections, including the side strippers) are the 9 structural optimisation variables. The objective function is to minimise hot utility demand, calculated using pinch analysis. The optimisation algorithm provides a systematic search for the set of operating and structural variables that maximise the performance of the system in terms of demand for fired heating. A minimum approach temperature of 30 °C is assumed for all heat exchangers when generating the grand composite curve.

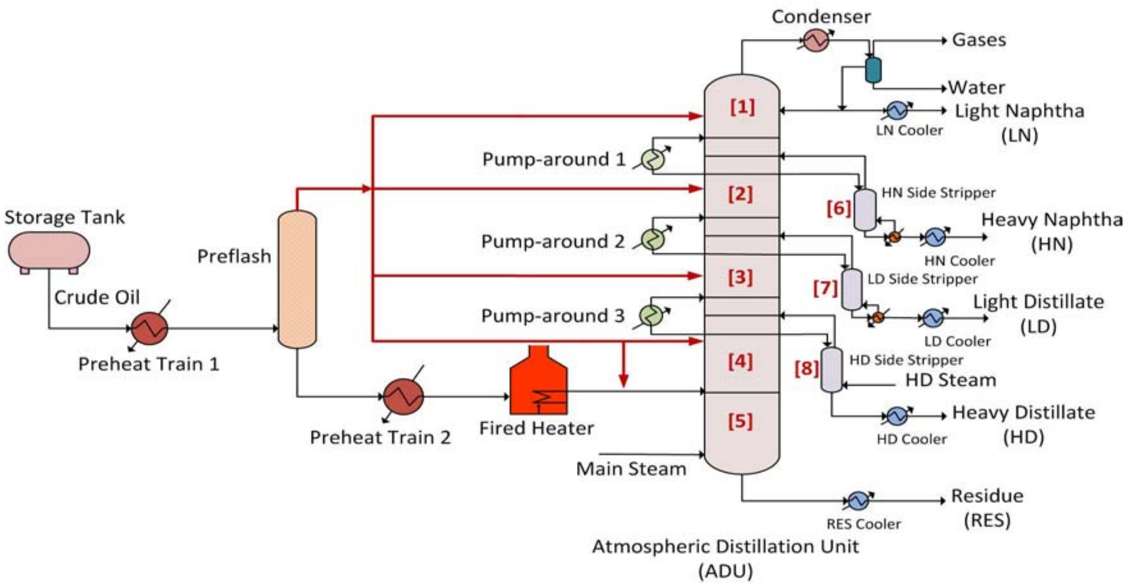

Figure 3: Crude oil distillation system with a preflash unit showing vapour feed locations

Optimisation is carried out as described in Section 2. Optimisation parameters for the genetic algorithm are: population size (100), maximum number of generations (500) and the objective function tolerance ($1{\cdot}10^{-10}$). Optimisation runs took 8 to 8.5 hours of CPU time on an HP desktop PC with Intel Core i5 processor running at 3.20 GHz and 16 GB of RAM.

A summary of the optimised operating variables is provided in Table 1 for: 1) the base case, where the column design is fixed (without a preflash unit); 2) the column design is fixed (no change in number of trays per section) and a preflash unit is added; 3) the column design is optimised for both operational and structural variables. Table 2 confirms that product specifications are satisfied within the tolerance (±10 °C) in all three cases. Product flow rates for all cases are presented in Table 3: the Residue flow rate is constant and other product flow rates change relatively little, as a consequence of product quality constraints. Table 4 provides detail of the base case (fixed) column structure and the optimised column structure. As shown in Table 1, introducing a preflash unit to the crude oil distillation system reduces the minimum hot utility demand by 20 %, compared to the base case (without a flash). The significant increase in the column feed temperature compensates for the large flow rate of vaporised crude oil that bypasses the fired heater and enters the column at a relatively low temperature (230 °C). Nevertheless, more high-temperature heat is recovered within the system: pump-around duties are reduced in PA1 and PA2, at lower temperatures, but increased in PA3, where higher-temperature heat is more useful. When a preflash is used and the column design is also optimised, there is a marginal decrease in demand for fired heating. This result suggests that the additional stages and new distribution of stages do not effectively improve the separation performance and heat recovery opportunities simultaneously.

Table 1: Summary of optimisation results

Variable	Units	Base Case (no flash)	Base Case (with flash)	Optimised Design
Main steam flow rate	kmol h^{-1}	1298	1287	1262
HD steam flow rate	kmol h^{-1}	275	200	209
PA1 duty	MW	9.3	8.5	7.2
PA2 duty	MW	10.1	8.7	8.8
PA3 duty	MW	10.5	12.0	11.9
PA1 ΔT	°C	23.7	31.7	33.4
PA2 ΔT	°C	36.2	31.8	31.1
PA3 ΔT	°C	39.8	16.9	21.3
Column feed temperature	°C	363	377	377
Flash temperature	°C	–	230	230
Reflux ratio		4.0	3.2	3.3
Vapour feed (section no.)		–	3	3
Minimum hot utility	MW	48.4	38.8	38.6

Table 2: Product quality ([a]: specified in HYSYS)

Product	Base Case (no flash) ASTM (°C)		Base Case (with flash) ASTM (°C)		Optimised Design ASTM (° C)	
	T5 %	T95 %	T5 %	T95 %	T5 %	T 95 %
LN	27	110 [a]	25	110	25	110
HN	134	196 [a]	133	196	133	196
LD	218[a]	300 [a]	218	300	218	300
HD	309	354 [a]	304	354	298	354
RES	362	754	361	754	361	754

Table 3: Product flow rates in $m^3\ h^{-1}$

Product	Base Case (no flash)	Base Case (with flash)	Optimised Design
LN	105	101	101
HN	84	89	89
LD	128	124	122
HD	53	57	58
RES	292	292	292

Table 4: Crude oil distillation column design (number of stages in each section)

Column Section	Number of trays		
	Base Case (no flash)	Base Case (with flash)	Optimised Design
1	9	9	6
2	8	8	10
3	10	10	11
4	9	9	9
5	5	5	10
6	6	6	3
7	7	7	8
8	5	5	7

For both cases with a preflash unit, the optimum flash temperature was 230 °C, the upper bound of the range; this suggests that the constraints on the search space should be revised. The insensitivity of the performance to the design of main column was unexpected. Further examination of capital–separation–energy trade-offs is planned, where the column capital cost and operating costs will be considered in the objective function.

4. Conclusions

This work proposes a new optimisation-based design methodology for a crude oil distillation system with a preflash unit including a wide set of operational and structural variables. The approach allows the vapour leaving the flash unit to be fed to a suitable location to the main column (according to the temperature of the tray) while column structure is modified simultaneously on each optimisation run. Pinch technology is applied using the Grand Composite Curve (GCC) to evaluate minimum hot utility demand of the system but it does not account for the fuel demand of the fired heater nor take into account the detailed design and costing of the heat recovery system.

The optimisation results show that adding a preflash unit – while applying product quality constraints and a flowrate constraint to the Residue and taking into account both operational and structural variables – can reduce the energy consumption of the system. It is evident that the simulation–optimisation approach is computationally intensive; this motivates the use of surrogate models, building on recent developments, e.g. Ibrahim et al. (2017).

Future work aims to extend the proposed design methodology to consider design of crude oil distillation systems with other pre-separation arrangements i.e. a prefractionation column. On the other hand, the objective function should be adapted to capture the trade-offs between yield and energy demand, e.g. by maximising net profit.

Acknowledgments

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