OPTIMISATION OF EXISTING HEAT-INTEGRATED REFINERY DISTILLATION SYSTEMS

Mamdouh Gadalla, Megan Jobson and Robin Smith

Department of Process Integration, UMIST, Manchester, UK

ABSTRACT

Existing refinery distillation systems are highly energy-intensive, and have complex column configurations that interact strongly with the associated heat exchanger network. An optimisation approach is developed for existing refinery distillation processes. The optimisation framework includes shortcut models developed for the simulation of the existing distillation column, and a retrofit shortcut model for the heat exchanger network. The existing distillation process is optimised by changing key operating parameters, while simultaneously accounting for hydraulic limitations and the design and the performance of the existing heat exchanger network. A case study shows that a reduction in energy consumption and operating costs of over 25% can be achieved.

KEYWORDS: heat integration, crude oil, retrofit, heat exchanger network, shortcut models.

INTRODUCTION

Crude oil distillation systems are among the largest energy consumers in the chemical industries. Crude oil distillation systems are complex configurations that interact strongly with the associated heat recovery systems. In crude oil distillation, the crude oil is preheated in two stages before entering the distillation column. The first stage is a heat exchanger network (HEN), where the oil is heated to an intermediate temperature by cooling distillation process streams and recovering the heat from condensers. Afterwards, the crude oil enters a furnace to reach the required processing temperature. The more fuel consumed in the furnace, the larger the operating cost. Any heat recovered from the distillation process reduces the utility consumption in the furnace. The energy efficiency of the distillation process can be improved by designing the distillation column to create opportunities for heat recovery and designing the HEN to exploit these opportunities.

Any change in the operating conditions of the distillation column changes the amount of heat that may be recovered, and therefore affects the energy efficiency of the distillation system (i.e. the distillation column and the associated HEN). These operating conditions include the feed preheating temperature, reflux ratios, pump-around temperature drops and liquid flows, and stripping steam flows. For example, when the temperature drop across the pump-around is reduced, the pump-around will operate at a higher temperature, which creates opportunities for heat recovery. Therefore, the energy efficiency of the distillation system can be improved by optimising all these variables simultaneously.

Objectives of retrofit projects in refineries include reducing energy consumption and increasing production capacity, in order to increase profit. The retrofit targets are preferably achieved by re-using the existing equipment more efficiently rather than installing new units and incurring greater capital investment. While fulfilling these retrofit objectives, existing equipment constraints, such as hydraulic capacity, must be met**.** Both these retrofit aims can be achieved by increasing the energy efficiency (and hence decreasing vapour loads) of the crude oil distillation column.

Existing retrofit methods do not consider the existing distillation columns simultaneously with the existing heat exchanger networks. Because they do not consider the hydraulic constraints of distillation columns, the retrofit modifications may require substantial capital investment. Furthermore, the heat integration targets for grassroots design, rather than the details of the existing heat network, are considered.

This paper presents an optimisation-based approach to retrofit design of refinery distillation systems, based on shortcut models for retrofit design of distillation columns and heat exchanger networks. This approach simultaneously considers the existing distillation column and the details of its associated heat exchanger network. It accounts for the hydraulic constraints of the distillation column. The approach is applicable for optimising existing refinery distillations for reducing energy consumption and operating cost, as well as for achieving a range of other retrofit objectives such as throughput increase, product specification changes and atmospheric emissions reduction.

LITERATURE REVIEW

Retrofit of refinery distillation systems has been studied by a number of researchers. Early research concentrated on proposing modifications to the distillation column and the heat exchanger network in order to reduce energy consumption. Sittig [1] suggested that, in order to improve the efficiency of the distillation system, new internals with higher efficiency should be installed and recommended the use of intermediate reboilers. Bannon and Marple [2] proposed other column modifications, such as the installation of pump-arounds. Adding pre-flash drums and pre-fractionator columns can save energy [3], as can adding pump-arounds and reducing operating pressure [4].

Pinch analysis principles guided many researchers [e.g. 5-7] to identify modifications to distillation columns for reducing energy consumption and improving the performance of the system. Liebmann [8] proposed a two-step approach for improving the performance of refinery distillation columns, based on insights derived from pinch analysis. Bagajewicz [9] proposed an approach for optimising existing refinery distillation columns, based on pinch analysis principles and rigorous model-based simulation.

Suphanit [10] developed an integrated approach to crude oil distillation system design. He used shortcut distillation models, pinch analysis and an optimisation framework, to generate energy-efficient grassroots column designs. This was the first method that systematically allowed the degrees of freedom in column design to be exploited to maximise the energy efficiency of a refinery distillation process. He did not consider any details of the HEN or application of his method for retrofit design.

Previous approaches have not considered the existing distillation column with the details of its existing heat exchanger network at the same time. Most methods suggested column modifications, which might require capital investment without the efficient re-use of the existing distillation equipment. Practical constraints, such as hydraulic limitations of the existing distillation column, have not been taken into account. This might lead to unfeasible designs. In addition, while heat integration targets obtained from pinch analysis were considered, the details of the heat recovery system were not. Many approaches used rigorous simulations, which lead to convergence problems, and are also time consuming. Finally, methods developed for grassroots design cannot be applied directly to retrofit refinery distillation columns.

In contrast, this paper presents a new optimisation-based approach for retrofit of refinery distillation columns in order to reduce energy consumption and operating cost. This approach considers the distillation column and its associated heat exchanger network simultaneously. Hydraulic limitations of distillation columns are accommodated in this retrofit approach. Other practical constraints, such as pump-around maximum duties can also be applied.

NEW OPTIMISATION APPROACH

In the new optimisation approach, the existing refinery distillation column and the associated heat exchanger network are considered simultaneously. The existing distillation column is considered through shortcut models, in which the number of stages and distribution of stages are specified. The details of the existing heat exchanger network are described using an area retrofit model that relates additional HEN area required to energy savings. The optimisation approach includes retrofit shortcut models for the distillation column and heat exchanger network, and uses sequential quadratic programming (SQP) to optimise the existing distillation and heat exchanger systems, while considering all design variables simultaneously.

During the optimisation, the existing distillation column (i.e. configuration, number of stages, distribution of stages, locations of condenser, reboiler, and pump-arounds) is fixed, as are the details of the existing heat exchanger network, including connections, existing exchangers and duties, existing areas. The optimisation approach changes all distillation column design variables to minimise the total annualised cost of energy consumption and additional HEN area required for retrofit.

The hydraulic limitation of the existing distillation column is included as a constraint in the optimisation.

Distillation Column Shortcut Model

Shortcut models for grassroot designs of distillation columns are well established and have been extensively applied [e.g. 10-17]. In these models, the number of theoretical stages, reflux ratio, reboiler duty, location of feeds and side draws, etc. is calculated for a given set of feed and product specifications. In contrast, models for retrofit design of distillation columns have not been published. In the optimisation of existing refinery distillation columns, these models are necessary to consider and describe the details of the existing distillation column. New retrofit shortcut models for steam-stripped and reboiled distillation columns are developed. These models represent the existing distillation columns during the optimisation; the models fix the existing column design and calculate the compositions and flow rates of the products, and the heating and cooling duties of the process.

In refinery distillation systems, when steam is used for stripping purposes, live steam is injected directly into the bottom of the column. Established shortcut models (e.g. Fenske-Underwood-Gilliland method) cannot be applied directly to design steam-stripped distillation columns [10]. For such cases, a retrofit shortcut model is developed for the top section, based on the modified Gilliland correlation [10], the Fenske and Underwood equations, and the material balance. In the bottom section, consecutive flash calculations can be used. Shortcut models are also developed for retrofit of distillation columns using reboilers. The models are an extension of those of Suphanit [10] and are based on the Gilliland and Kirkbride correlations, the Fenske and Underwood equations, and the material balance equations of the light and heavy key components. Details of the models are published separately [18].

Refinery distillation systems contain both steam-stripped sections and reboilers. Fig. 1 shows a typical refinery distillation process. The shortcut models developed for columns with reboilers and steam-stripped columns combine to give a shortcut model for refinery distillation columns. The column model is applied as follows:

1. The complex column is decomposed into the equivalent sequence of simple columns. This facilitates the analysis of the distillation process.
2. The existing number and distribution of stages, and the locations of reboilers, the condenser and pump-arounds are fixed for each simple column.
3. The shortcut model is applied to each simple column in the existing distillation system. It calculates the product compositions, flows and temperatures, and the condensing and reboiling duties.

The strength of the approach is that it can accommodate any configuration of columns (e.g. prefractionator, side-stripper, side-rectifier, direct and indirect sequence of columns), both steam stripping and indirect heating (reboiling), and is specifically designed to describe existing distillation columns.

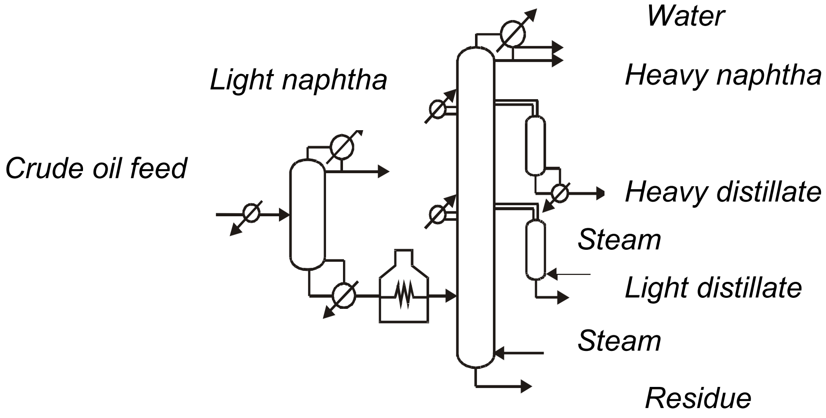


Fig. 1 Crude oil distillation unit

Heat Exchanger Network Model

The literature is rich in methods and approaches for retrofit design of heat exchanger networks [e.g. 19-24]. None of these methods present a systematic approach to the retrofit design of both the process (e.g. the distillation column) and the associated HEN. There are interactions between the distillation column and the heat exchanger network that significantly affect the energy consumption. In this work, an area retrofit model is proposed for the heat exchanger network. This model relates the additional exchanger area required for retrofit to the energy consumption of the distillation column. The form of the area retrofit model is very simple, e.g. Area = a $(\Delta \text{Energy})^{b}$, but the parameters (a, b) are obtained through detailed retrofit analysis and comprehensive consideration of the design of the existing HEN using network pinch analysis [25]. The retrofit model includes the details of the existing heat exchanger network, such as existing exchanger matches, existing areas and duties, existing utility consumption, and all possible retrofit modifications. The area retrofit model is included in the optimisation framework. It is a powerful, yet simple, way of representing the complexities of the existing HEN and all possible HEN modifications that allows simultaneous optimisation of the distillation column operating conditions.

Hydraulic Constraints of Distillation Column

Retrofit projects of refinery distillation processes are highly constrained by the hydraulic capacity of the distillation column. An existing distillation column section has a fixed diameter, which creates hydraulic constraints. Retrofit objectives can be achieved whenever the diameter required for vapour flow does not exceed the existing diameter. At flow rates exceeding these hydraulic limitations, the distillation column becomes bottlenecked and flooding occurs. To avoid flooding, significant capital investment will be required. In this work, the hydraulic limitations of the distillation columns are taken into account in the optimisation framework. During the optimisation, the diameter required for separation in each section is calculated from flooding correlations and vapour flows inside the column. Then, the hydraulic limitations (e.g. the existing diameters) of the existing distillation column are applied as constraints to the optimisation to keep the required diameter of each section less than the existing diameter. This consideration ensures that process modifications resulting from the retrofit design procedure are feasible with respect to the column hydraulics.

Simultaneous Optimisation Framework

An overall model for optimisation of an existing heat-integrated distillation process is formulated by combining the column retrofit model and the area retrofit model for the heat exchanger network. Since the models for the distillation column and the existing heat exchanger network are non-linear, the optimisation problem is a non-linear programming (NLP) problem. The optimisation uses a successive quadratic programming SQP solver. In particular, the subroutine E04UCF of the NAG Fortran library [26] is used to implement the Quasi-Newton method [27] in the solution.

The optimisation framework proposed for refinery distillation columns is shown in Fig. 2. As shown in the figure, the column retrofit model and the HEN model are solved simultaneously within a black box in the optimisation framework. The cost model calculates the annual cost of the energy consumption and the capital costs for additional exchanger area and HEN retrofit modifications. The lower and upper boundaries of each optimisation design parameter need to be provided. The hydraulic limitations of the existing distillation column are applied to the optimisation as a constraint. Any practical constraints of the existing HEN, such as maximum duty of pump-arounds, may be applied in the optimisation. The objective of the optimisation is the minimisation of the objective function, i.e. the total annualised cost of the energy consumption and additional HEN area required for retrofit.

During the optimisation, the existing distillation column is fixed, and the details of existing heat exchanger network are accounted for. All operating variables are optimised simultaneously to minimise the objective function. When a constraint is violated, a penalty value is added to the objective function.

The optimisation of an existing refinery distillation column results in a set of optimum column operating conditions with minimum energy consumption and minimum additional area in the associated heat exchanger network.

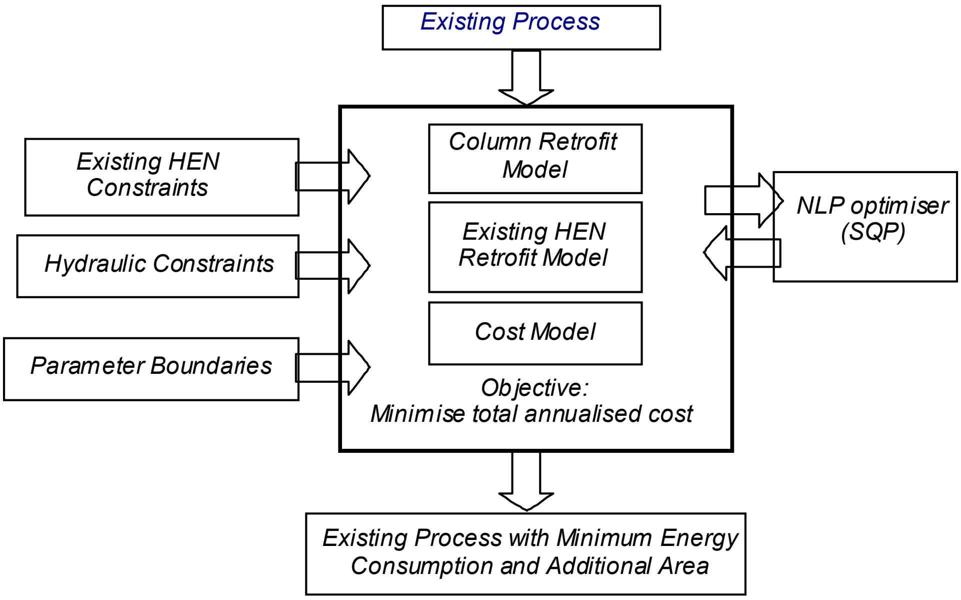


Fig. 2 Optimisation framework of heat-integrated distillation systems

CASE STUDY

The new optimisation approach is applied for retrofit of an atmospheric crude oil distillation unit. The retrofit objective of this case study is to reduce the current energy consumption and operating cost of an existing crude oil distillation unit (Fig. 3). The distillation aspects of the case study are based on a textbook example of an atmospheric crude oil distillation tower [28]; the HEN is based on an industrial example. The crude oil mixture is the assay of Tia Juana Light (Venezuela).

The unit processes 100,000 barrels per day of crude oil to produce light naphtha (LN), heavy naphtha (HN), light distillate (LD), heavy distillate (HD) and residue. The column uses three side strippers and three pump-arounds. The existing operating conditions of the distillation column are listed in Table 1. These operating conditions include feed preheating temperature, flow rate of liquid through each pump-around, temperature drop along each pump-around, steam flow rate to each section, and reflux ratio. The diameter of each column section is given in Table 2. The existing heat exchanger network is illustrated in Fig. 4; the HEN contains 27 exchangers, with a total area of 4,000 m^2. The energy consumption of the existing distillation column is 99 MW; the utility cost is $17 \cdot 10^6$ £/yr.

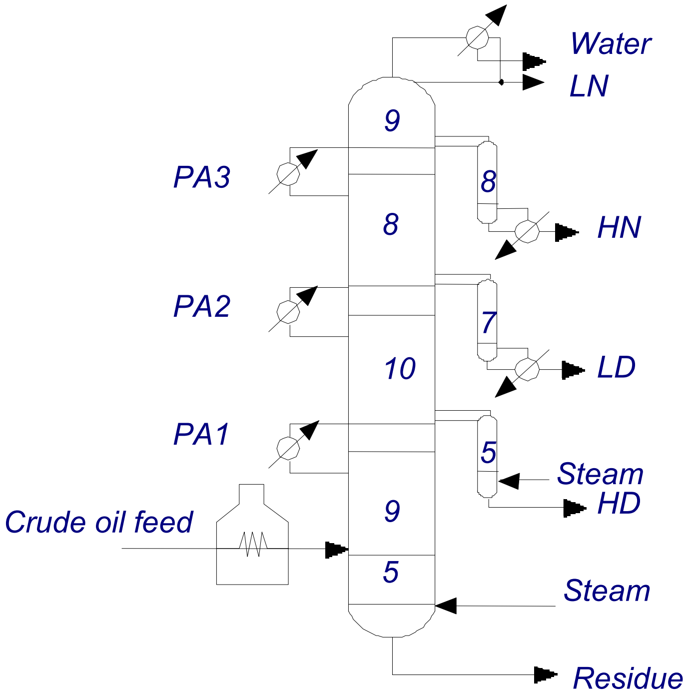


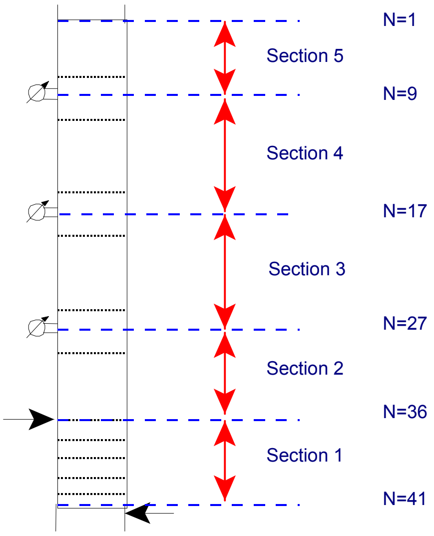
Fig. 3 Existing atmospheric crude oil distillation column, showing number of stages in each column section

Table 1 Operating conditions of the existing distillation column

Variable		Value
Feed preheat temperature	(^{o}C)	365
PA1 liquid flow	(kmol/h)	2187
PA2 liquid flow	(kmol/h)	2306
PA3 liquid flow	(kmol/h)	5791
PA1 temperature difference	(^{o}C)	30.0
PA2 temperature difference	(^{o}C)	50.0
PA3 temperature difference	(^{o}C)	20.0
Main steam flow	(kmol/h)	1200
HD-stripper steam flow	(kmol/h)	250
Reflux ratio (R/R_{min})		1.20

Table 2 Hydraulic constraints of the existing distillation column

Section	Diameter
1	5.5
2	8.0
3	7.5
4	7.5
5	6.7



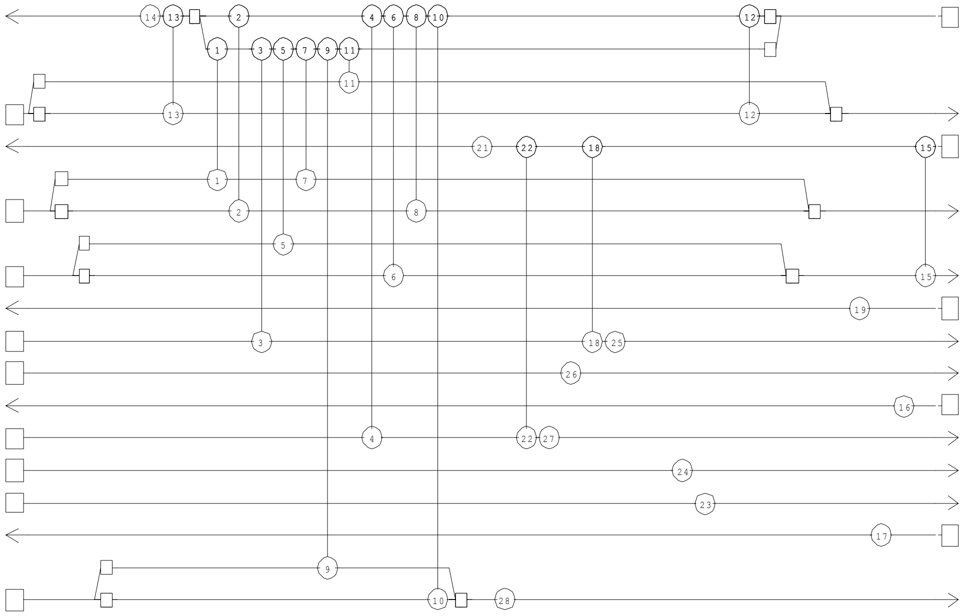


Fig. 4 Existing heat exchanger network

RESULTS

Prior to the optimisation of the existing crude oil distillation unit, an extensive retrofit study is carried out on the existing HEN, using network pinch [25], to obtain the area retrofit model. This study fixes the existing exchanger matches, and allows network modifications to reduce the energy consumption. The retrofit data obtained is then regressed to calculate the retrofit parameters of the area retrofit model.

$$\text{Area} = 1.0738\,(10)^{6} \times (\Delta\ \text{Energy consumption})^{-1.2298} \qquad (1)$$

where the units of Area are m^2 and those of Energy consumption are MW.

For the existing refinery distillation unit, the operating variables of the distillation column are then optimised simultaneously to minimise the total annualised cost. During this simultaneous optimisation, the column configuration (i.e. locations of condenser, pump-arounds and reboilers) is fixed. The product specifications in terms of component recoveries are kept unchanged, while the product flows are allowed to change within a specified limit. In addition, the calculated column diameters are constrained, so that the existing hydraulic limitations are not exceeded. The existing matches of the heat exchanger network are also fixed, but the duties are allowed to vary. The optimisation solution takes approximately 2663 CPU seconds on 1.0 GHz, 256 MB RAM Pentium III PC.

The optimisation of the existing refinery distillation column results in the optimum set of operating variables, listed in Table 3. The energy-related and economic results are summarised in Table 4. It can be seen that the energy requirement is reduced significantly from 99 MW to 72 MW. No significant modifications to the column are required. The modifications required to the existing network are additional area to some existing exchangers and the resequencing of an existing exchanger, as shown in Fig. 5. A very low payback period is projected. The product flows of the optimum are shown in Table 5, and compared with those of the base case; the maximum deviation in product flows, compared to the base case, is less than 1%.

Table 3 Optimum operating conditions

Variable		Value
Feed preheat temperature	(^{o}C)	370
PA1 liquid flow	(kmol/h)	2027
PA2 liquid flow	(kmol/h)	2027
PA3 liquid flow	(kmol/h)	6992
PA1 temperature difference	(^{o}C)	33.5
PA2 temperature difference	(^{o}C)	30.5
PA3 temperature difference	(^{o}C)	18.6
Main steam flow	(kmol/h)	1085
HD-stripper steam flow	(kmol/h)	213
Reflux ratio (R/R_{min})		1.05

Table 4 Optimisation results

Parameter		**Existing**	**Optimum**
Energy consumption	MW	99	72
Energy saving	MW	-	27
Energy cost	10^6 £/yr	17.50	12.66
Stripping steam cost	10^6 £/yr	2.90	2.59
Saving in operating cost	10^6 £/yr	-	5.15
Additional HEN area	m^2	-	1411
HEN modification		-	Resequence
HEN capital investment	10^6 £/yr	-	0.95
Payback	yr	-	0.2
ΔT_{min}	^{o}C	35	25

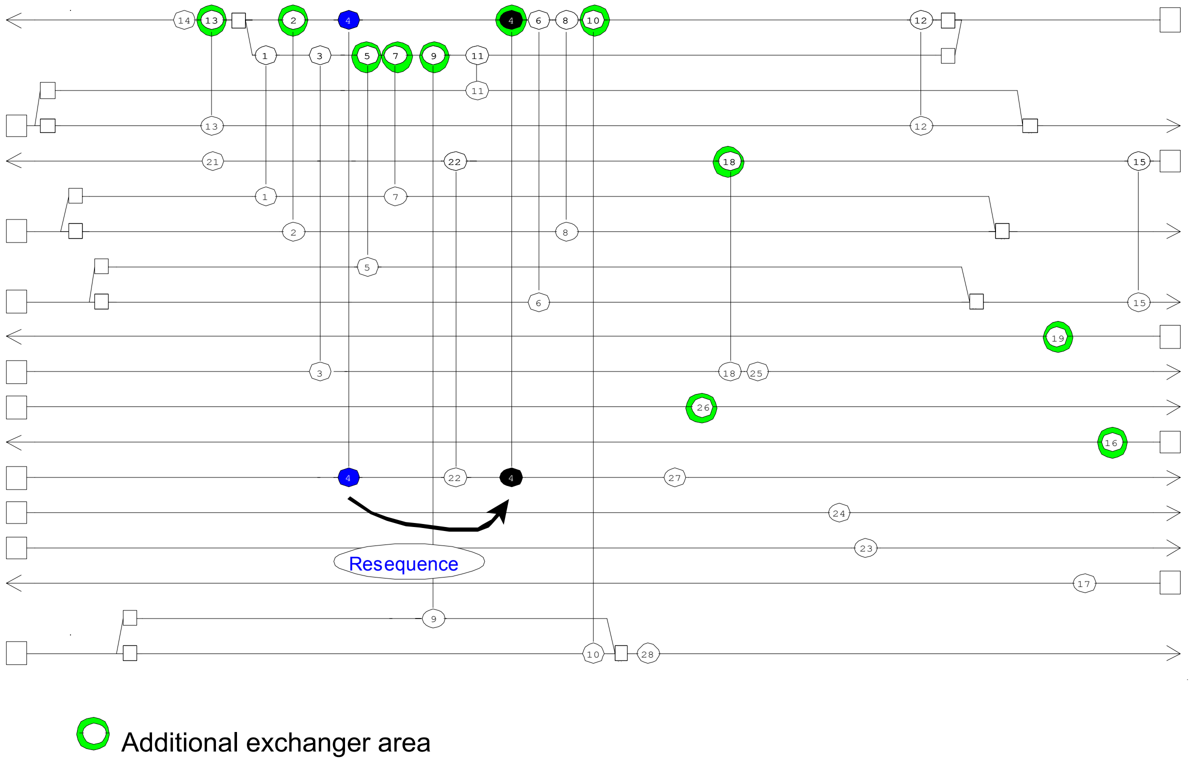


Fig. 5 Optimum heat exchanger network

Table 5 Product flowrates before and after process optimisation

Product		Base case	Optimum
Light naphtha (LN)	kmol/h	680.7	681.9
Heavy naphtha (HN)	kmol/h	493.5	495.3
Light distillate (LD)	kmol/h	652.8	651.2
Heavy distillate (HN)	kmol/h	149.8	150.2
Residue (Res)	kmol/h	633.9	632.1

CONCLUSIONS

An optimisation approach for retrofit of refinery distillation columns has been developed. This approach can optimise an existing heat-integrated refinery distillation column, while taking into account its hydraulic limitations. A new set of retrofit shortcut models for describing existing distillation processes and associated heat exchanger networks (HEN) has been developed and included in the optimisation framework. The model used for the HEN considers the design and configuration of the existing HEN, and various retrofit design options, rather than simply using targets for grassroots design obtained by pinch analysis, as is the case in the previous methods.

The approach can be applied to various configurations of refinery distillation columns for reducing energy consumption and operating cost. A comprehensive retrofit study of the existing HEN is used to find the retrofit area model parameters. A case study showed a significant reduction in the energy consumption and operating cost of an existing crude oil distillation column. By changing the objective function, other retrofit goals (e.g. changing product specifications, increasing throughput, decreasing greenhouse emissions) can be achieved. While the optimisation approach has been developed for the retrofit of heat-integrated refinery distillation systems, it is more generally applicable.

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