CHEMICAL ENGINEERING TRANSACTIONS
VOL. 52, 2016

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Peng-Yen Liew, Jun-Yow Yong, Jiří Jaromír Klemeš, Hon Loong Lam

ISBN 978-88-95608-42-6; **ISSN** 2283-9216
DOI: 10.3303/CET1652149

Investigation of Heat Recovery with Pump-Arounds at a Crude Oil Atmospheric Distillation Tower

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Effect of application of pump-arounds in an atmospheric crude oil distillation column on tower parameters as well as on the heat balance of the whole unit was investigated. Model of three cases was prepared Base case without, while Case1 with one and Case2 with two pump-arounds. After establishing the models Energy Integration studies were done in every case. Results showed that by applying pump-arounds the required tower diameter considerably decreased from 5,180 mm to 4,570 mm or 4,270 mm depending on its number. Another advantageous effect of using pump-arounds was that the internal flow rate of the distillation column became more uniform. However, it should be noticed that the tray design of pump-around section required special consideration due to the high liquid loads. Results of Energy Integration studies to be done at Δt_{min}= 20 °C and with overall heat transfer coefficient of 0.3 kW/m^{2}°C showed that both the external heating and cooling requirements significantly decreased (Q_C: 23,256 kW → 14,207 kW / 13,569 kW; Q_H: 23,256 kW → 14,207 kW / 13,569 kW) meantime the attainable process/process heat exchange increased (33,475 kW → 45,238 kW / 45,434 kW). The temperature of cold stream (e.g. crude oil) leaving the pre-heat train also improved (147 °C → 180°C) by realizing the heat recovery at higher temperature levels. With implementing pump-arounds (Case1/Case2) the total process/process heat exchanger area, which calculated with using the Composite Curves, were higher than that was in Base case. Taking everything in account it can be stated implementation of pump-around system in the crude oil distillation tower had clear positive effect on both the capital and operating expenditures.

1. Introduction

Nowadays, the harsh economic environment forces the petroleum refining companies to strong competition on the market of refined products. Decrease in operating expenditures (OPEX) of refineries is inevitable to survive this time period. The energy cost is the largest operating cost in a refinery and it can take up to two-thirds of the total OPEX. Most of the energy cost makes up the fuel cost including heating of process streams and generating both process and heating steam. Therefore, improvement in the energy efficiency contributes to increase the profitability of a refinery. Additionally, the lower energy usage also means less emission in greenhouse gases (mainly CO_2) and other flue gases (e.g. NO_x, SO_x), which decreases the impact of the crude oil processing on the environment both local and global levels.

The crude oil distillation unit is the greatest energy consumer in a refinery. This is because almost all of hydrocarbon streams (crude oil, natural gas liquid, gas condensate etc.) entering into the refinery go through this plant, and the streams are heated up as high as 360 °C in the atmospheric and 410 °C in the vacuum furnaces (Chaudhuri, 2011). This clearly shows even a small energy improvement resulting considerable resource saving. Several papers were published in the recent years dealing with energy improvement of crude oil distillation units; some of them studied the possible revamp of an existing unit (including the heat exchanger network and distillation towers) while others were investigated the optimal design of a grass-root unit.

Kamel (Kamel et al., 2013) introduced a new revamping methodology for optimizing both HEN and distillation columns simultaneously in an existing unit resulting 17 % savings in energy consumptions. Varga (Varga et

Please cite this article as: Varga Z., Lóczi K., 2016, Investigation of heat recovery with pump-arounds at a crude oil atmospheric distillation tower, Chemical Engineering Transactions, 52, 889-894 DOI:10.3303/CET1652149

al., 2010) reported results of a study for increasing capacity and improving energy efficiency in a crude distillation unit processing different types of crude oil. Result showed after optimizing the HEN and topping column 10 - 12 % decrease in the CO_2 emission can be obtained.
Despite large number of papers investigating crude oil distillation unit information about the optimization of the pump-arounds of distillation tower were scarce. Gadalla (Gadalla et al., 2013) studied the effect of the flowrate of pump-around on the minimum energy consumption. It found that the minimum energy consumption changed according to a minimum curve displaying it is an optimum value in the pump-around flowrate.
The our aim was to investigate the effect of various pump-around arrangements on the minimum heating and cooling requirements, heat exchanger area, and tower parameters of an atmospheric crude oil distillation unit.

2. Methods

Figure 1 shows the investigated cases. First the distillation tower was modelled without using any pump-arounds (Base Case). Then the heat load of the condenser (C1) was decreased by using one (PA1) and two (PA1 and PA2) pump-arounds (Case1 and Case 2).
In each case the crude oil was introduced at 20 °C into the unit and it was pre-heated to 130 °C before entering the Desalter. Temperature of desalted crude oil was increased further up to 350 °C and introduced into the atmospheric tower in which crude oil was separated into fuel gas, naphtha, kerosene, light and heavy gas oils, and atmospheric residue. The atmospheric distillation column constitutes 32 theoretical stages and consists of a partial condenser, and coupled side columns with 4 stages to set the initial boiling point of the kerosene and light gas oil products. The feed to the atmospheric distillation column enters on stage 30. Steam stripping that aids enhancement of volatility via the reduction of partial pressure is facilitated by using steam at 320 °C and 3.0 bar. The average pressure drop of the atmospheric distillation tower is taken as 0.8 bar with the first stage at 2.0 bar, and the bottom stage pressure of 2.8 bar.
Side stripper 1 was fed with liquid drawn from stage 9 of the main column. The lighter product produced in the side column was fed to stage 8 of the main column and the bottom product was the kerosene stream. The heat required to boil up the light hydrocarbons was provided with a reboiler (R1). Side stripper 2 was fed with liquid drawn from stage 15 of the main column. The lighter product produced in the side column was fed to stage 14 of the main column and the bottom product was the light gas oil stream. Superheated steam was used for providing heat and reducing partial pressure of hydrocarbons.
Heat was removed from the tower with the condenser and products at the Base case. A pump-around (PA1) circulating liquid from stage 17 to stage 16 was facilitated to provide internal reflux and utilize heat at higher temperature level at Case1. Temperature drop of PA1 was set to 40 °C. Second pump-around (PA2) was implemented at Case2, which circulated liquid from stage 24 to stage 23 with 20 °C temperature drop. Application of two pump-arounds made it possible to utilize heat at various temperature levels and provided smoother internal flow in the column. Heat duties of PA1 and PA2 were set to the maximum possible values those did not have any detrimental effects on the quality of products to be defined with the distillation curves.
Temperatures of products at the battery limit of the atmospheric distillation unit were the following 50 °C of naphtha, 40 °C of kerosene, 50 °C of light and heavy gas oils, and 322 °C of atmospheric residue.
Detailed model of the distillation system including tower diameter calculation was prepared with PROII 9.2 process engineering tool.
Data of product and pump-around streams (inlet and target temperatures, enthalpy flows) was used as input for the Pinch Analysis. The minimum temperature approach was selected in 20 °C. The preparation of Composite Curves, calculation of minimum heating and cooling requirements as well as heat exchanger area estimation (at overall heat transfer coefficient of 0.3 $kW/m^{2}°C$) was done on the work of Linnhoff and presented in Chapter 2 of the book written by Klemeš and co-workers giving detailed description of the Pinch Analysis (Klemeš et al., 2014). It contains the background and the main steps as well as an illustrative example of the heat exchanger network analysis.

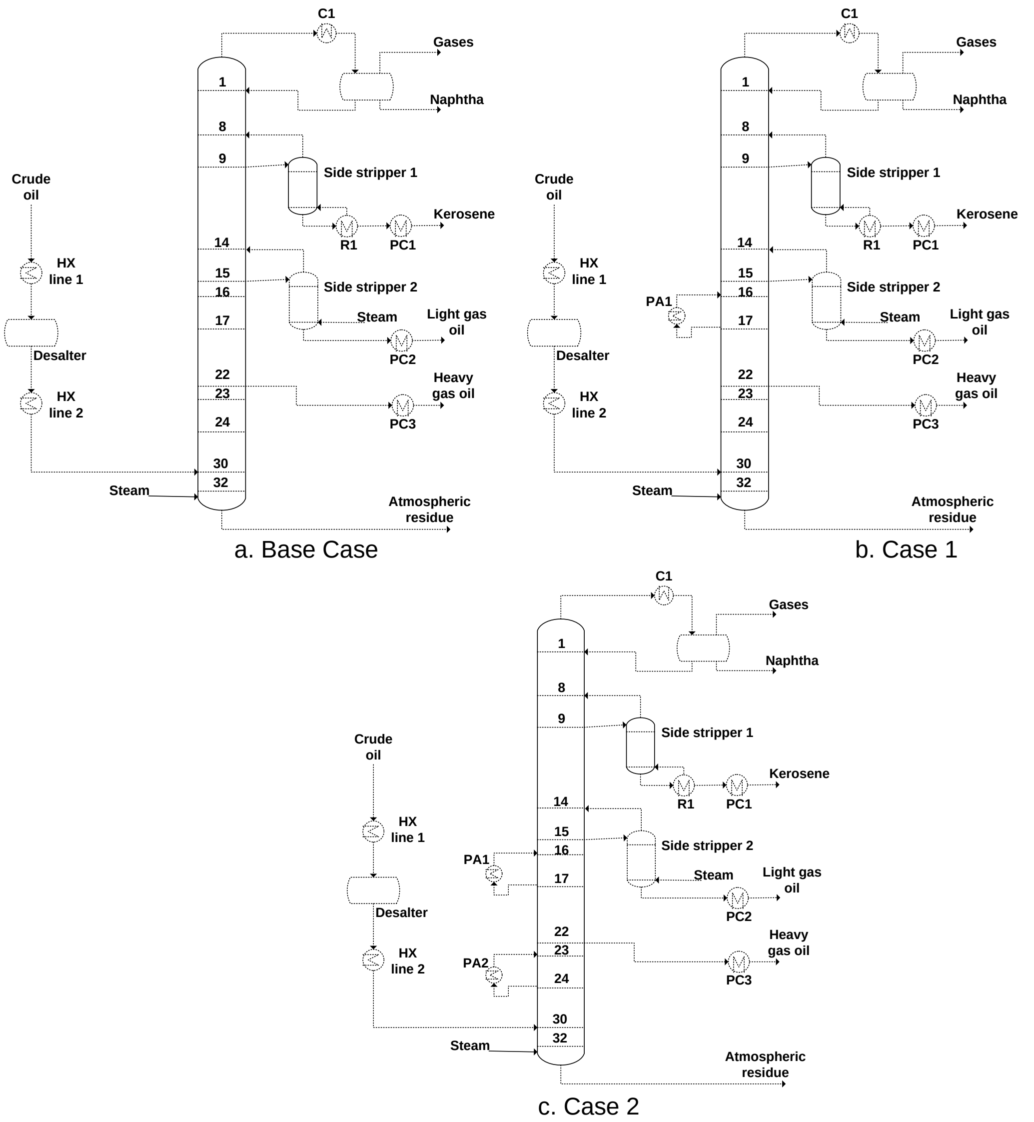

Figure 1: Flowsheet of investigated cases

3. Results and discussion

Figure 1 shows the three crude oil distillation tower arrangements those were investigated during the study. At first the distillation column was modelled without applying any pump-arounds (see Base case). Then a pump-around (PA1) being placed right below the light gas oil draw tray was incorporated into the model (Case 1). Finally, the model used at Case 1 was extended with another pump-around (PA2) to be set right below the heavy gas oil draw tray (Case 2). Main column parameters of the selected cases were summarized in Table 1, while the calculated tray loads (both vapour and liquid) are displayed in Figure 2.

Data of Table 1 show that top and bottom temperatures were practically not changed with using pump-arounds. However the draw tray temperatures were influenced such a way that increase in the pump-around heat duties resulted lower product temperatures, which decreased the recoverable heat flow at cooling the products down to the storage temperatures. In relation to the heat duties it can be seen that the heat load of the condenser decreased with almost 24 % at Case 1 and more than 25 % at Case 2. It means that the quantity of low value heat, which can only be used for boiler feed water pre-heating or in low temperature process/process heat exchange, was reduced. Data also show that the kerosene reboiler duty was increased significantly. The reason of this is that the kerosene draw tray temperature decreased in Case 1 and Case 2 while the kerosene reboiler temperature (227 °C) was kept constant in every case to set the initial boiling point of the products, consequently the heat to be added into the reboiler should be increased. It results higher heat exchanger area as well as decrease in the recoverable high temperature heat.

Table 1: Main tower parameters obtained at the selected cases

Parameter	Base case	Case1	Case2
Column diameter, mm	5,180	4,570	4,270
Column outlet temperature, °C			
Top vapour	135	133	133
Kerosene	227	227	227
Light gas oil	252	221	217
Heavy gas oil	306	306	284
Atmospheric residue	322	322	322
PA1	n.a.	264	257
PA2	n.a.	n.a.	297
Heat duty, kW			
Condenser	39,951	30,561	29,804
Kerosene reboiler	752	1,365	1,423
PA1	n.a.	12,500	7,222
PA2	n.a.	n.a.	6,667

The maximum heat duty of PA1 that can be recovered without causing negative effect on the product quality was 12,500 kW at Case 1. This heat flow was available at high temperature and it can be utilized for pre-heating the crude oil. The difference in condenser heat duties (9,390 kW) being obtained for Base case and Case1 was lower than the heat duty of PA1 (12,500 kW). It clearly shows that the attainable reduction in the condenser duty was lower than the duty of the pump-around. This is because one hand the greater heat duty of the kerosene reboiler and on the other hand the lower draw tray temperatures. At Case 2 the maximum heat duty of pump-arounds (PA1 and PA2) those can be reached without causing negative effect on the product quality was 7,222 kW and 6,667 kW, respectively. The heat duty of PA2 was lower than that of PA1 was for every investigated case. The sum of heat flows of PA1 and PA2 (13,889 kW) was higher than that of PA1 alone at Case 1 (12,500 kW) was. Therefore, application of two pump-arounds resulted better heat recovery at higher temperatures as well as considerable increase in the energy efficiency. Similarly to Case 1 the attainable reduction in the condenser duty (10,147 kW) was lower than the sum of pump-around duties was. This is because one hand the greater heat duty of the kerosene reboiler and on the other hand the lower draw tray temperatures.

Figure 2 displays both the vapour and liquid loads of trays. As regards the vapour load of trays (Figure 2(a)) it can be seen its values were considerable higher for Base case than in the other two cases in tray number range of 1 - 17. By applying one or two pump-arounds (Case 1 and Case 2) the vapour load became smoother along the length of the column. In respect to liquid load it can be stated that the use of pump-arounds resulted more even liquid load, except in the pump-around zones where the internal liquid flow was considerable increased due to recirculating the majority of the liquid flowing down to pump-around trays. This requires special tray design to avoid flooding. Column diameters being calculated for the selected cases (Table 1) shows the implementation of pump-arounds, which resulted in more uniform tray loads, allowed using smaller tower diameter, consequently the capital expenditures would also be lower.

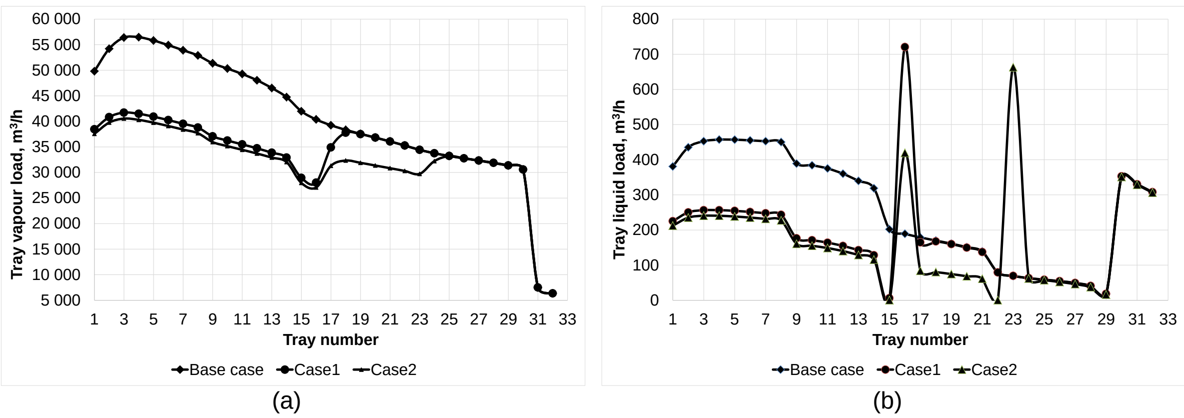

Figure 2: Tray loads of selected cases (a) vapour load, (b) liquid load

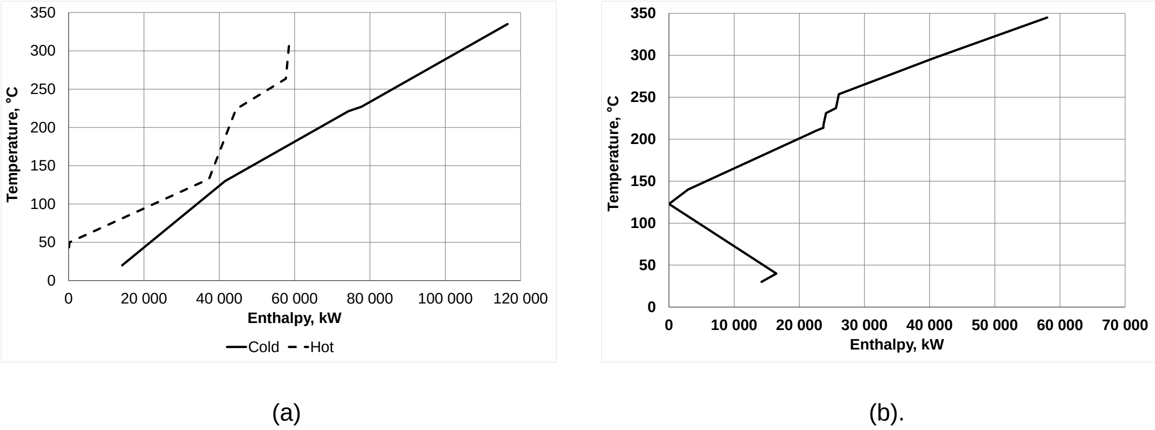

Figure 3: Composite and Grand Composite Curves for Case 1

The crude oil distillation tower is thermally coupled to the crude oil preheat train through process/process heat exchangers. Therefore, the implementation of pump-arounds also influences the energy efficiency of the whole unit. In order to count the effect of implementation of pump-arounds on the heat balance of the unit energy integration was prepared for every case. Figure 3 shows the Composite and Grand Composite Curves calculated for Case 1. We obtained similar ones for the Base case and Case 2. Most important results of the energy integration studies are summarized in Table 2.

Data show that Pinch temperatures were scarcely changed by the implementation of pump-arounds; however they showed a tendency of decrease. In regard to heat duties it can be stated that both the minimum cooling and minimum heating requirements decreased for Case1 and Case2. The reason of this is that the heat duty of the process/process heat exchange became significantly greater above the Pinch by incorporating PA1 and PA2 providing heat at higher temperatures. This clearly shows that using heat available at higher temperature level (264 °C for Case1 and 257 °C / 297 °C for Case2 vs. 135 °C for Base cease) considerably increased the heat recovery at above the Pinch resulting less external heating requirement e.g. duty of fired heater. This means not only reduction in the operating expenditures but less flue gas emissions (CO_2, NO_x etc.), too. Another advantageous effect of the greater heat recovery was the higher outlet temperature (180 °C for both Case1 and Case2) of cold stream e.g. crude oil.

Data of Table 2 also display that the possible process/process heat exchange slightly decreased at below the Pinch, which was caused by shifting the duty of the condenser to the pump-arounds. Despite this reduction the outlet temperature of hot stream e.g. product streams became lower (92 °C for Base case → 81 °C for Case1/Case2).

Calculation of heat exchanger area was done based on the Composite Curves considering 0.3 kW/m^2°C of overall heat transfer coefficient and perfect counter current heat exchange.

Table 2: Most important results of the energy integration studies at ΔT_{min} =20 °C

Parameter	Base case	Case1	Case2
Pinch temperature, °C	125	123	122
Heat duty, kW			
Min. Heating, Q_{Hmin}	68,181	58,046	57,057
Min. Cooling, Q_{Cmin}	23,256	14,207	13,569
Process/Process			
Above pinch	9,868	22,128	22,324
Below pinch	23,607	23,110	23,110
HX area, m^2			
Process/Process			
Above pinch	626	1,122	1,049
Below pinch	1,941	2,088	2,104
Outlet temperatures, °C			
T_{cold_out}	147	180	180
T_{hot_out}	92	81	81

Results summarized in Table 2 show that the required heat exchanger area of Pinch above almost doubled on installing one or two pump-around circulation systems. The reason for this is definitely the greater process/process heat exchange. At Pinch below it can be seen that despite the lower process/process heat exchange of Case1 /Case 2 the required heat exchanger areas were higher comparing to that of the Base case. This is because by applying pump-arounds the driving force of the heat exchange became smaller.
As shown in the aforementioned results the implementation of pump-around system into the atmospheric crude oil distillation tower was advantageous, because higher heat recovery and pre-heat temperature can be obtained. In comparing of Case 1 and Case 2 (one or two pump-arounds) it can be stated that the implementation of two pump-arounds resulted less external heating and cooling as well as higher process/process heat exchange above the Pinch. In respect of heat exchange areas it can be said that despite the higher heat recovery of Case 2 the calculated heat exchange area was lower than that of Case 1 at above the Pinch, which was caused by the more uniform temperature distribution obtained for Case 2. At below the Pinch the calculated process/process heat exchanger area of Case 2 was somewhat higher than that of Case 1 at the same heat recovery level due to the lower driving force. Comparing the total process/process heat exchanger area calculated for Case 1 and Case 2 it can be stated that it was smaller in the latter case resulting lower capital expenditures. Data of Table 2 show that both the calculated hot and cold temperatures were the same for Case 1 and Case 2, consequently this parameter did not make possibility for any differentiation between the investigated cases.
Based on the results of the study the following can be highlighted. Implementation of pump-around system in the crude oil distillation tower showed clear positive effect on both the capital and operating expenditures. At the present level of details of the calculation using of two pump-around systems seems to be far preferable, but the detailed design of the heat exchanger network would be shown clear picture about it. Additionally, the optimal sharing of heat load between PA1 and PA2 should be determined with carrying out further investigations.

4. Conclusions

In a petroleum refinery the crude oil distillation unit belongs to the most energy intensive processes, accordingly its energy efficient operation is inevitable for reducing the operation expenditures. Additionally, over the advantageous economic effect improving in the energy efficiency also contributes to reducing in the emission of flue gases. The accomplished study aimed at investigating the effect of applying pump-around on parameters of the distillation tower and heat exchanger network, as well. Results clearly showed that incorporating pump-arounds, which provide heat at higher temperatures, into the crude oil distillation unit resulted positive changes in the internal flow rates of the column (both vapour and liquid) and increased the recoverable heat in the heat exchanger network.
However, the advantageous numbers of pump-arounds as well as the optimal heat load distribution between them require further investigation.

Reference

Chaudhuri U.R., 2011, Fundamentals of petroleum and petrochemical engineering, CRC Press, Boca Raton, FL, USA.

Gadalla M., Kamel D., Ashour F., Nour El din H., 2013, A New Optimisation Based Retrofit Approach for Revamping an Egyptian Crude Oil Distillation Unit, Energy Procedia, 454 – 464.

Kamel D., Gadalla M., Ashour F., 2013, New retrofit approach for optimisation and modification for a crude oil distillation system, Chemical Engineering Transactions, 35, 1363-1368 DOI:10.3303/CET1335227

Klemeš J.J., Varbanov P.S., Alwi S.R.W., Manan Z.A., 2014, Process Integration and Intensification: Saving Energy, Water and Reseources, De Gruyter, Berlin.

Varga Z., Rabi I., Kubovics Stocz K., 2010, Process simulation for improve energy efficiency, maximize asset utilization and increase in feed flexibility in a crude oil refinery, Chemical Engineering Transactions, 21, 1453-1458 DOI: 10.3303/CET1021243