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Pinch Analysis Applied to Atmospheric Distillation Column

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To increase the efficiency of industrial processes, mainly in petroleum refineries, strategies for energy optimization are being developed. Thus, there is a need for energy consumption analysis in terms of the loss level and to select a procedure to recovery that loss. The analysis involves a flow rate study, based on energy balances, and the best strategy for energy use can be established with the installation of heat exchanger networks (HEN). With the use of this procedure, we can reduce the operational costs through a reduction in the energy consumption. The study reported herein relates to a refinery atmospheric distillation column, using pinch technology, based on the law of conservation of energy. The pre-flash, atmospheric distillation column and heat exchanger networks were evaluated. The data considered were collected from a refinery in Angola, over 30 days and the results were used to obtain the mass and energy balances. The flow sheet of the process and the relations between the operational parameters in industrial equipment were previously evaluated. The results for the energy balances were used in an integration study, supported by pinch analysis using spreadsheet software, and the data presented as composite, grand composite and cascade curves. A heat exchanger battery, based on pinch analysis, was used to construct the new networks of energy integration. After the assessment of each network with 4 to 12 heat exchangers, optimization was carried out to identify which offers the best energy consumption. The proposed network is evaluated in terms of the reduction in energy consumption, least number of heat exchangers and network optimization. With this methodology, reductions in the energy consumption of 785.4 KW (hot) and 1277.1 KW (cold), can be achieved. In addition, the optimization strategy adopted herein allowed an increase in the temperature from 280°C to 301°C.

1. Introduction

The complexity associated with a petroleum refinery presents challenges with regard to the need to develop technologies and innovations aimed at reducing the operations costs through optimization and the reuse of energy through an integration network. The strategies for energy optimization have a direct impact on energy consumption, which can result in the improvement of economic sustainability and industrial competitiveness[1].

Thus, research needs to be focused on the quality and operational efficiency of industrial processes, in order to reduce production costs and improve the quality of the products. In this context, was employ energy integration, using an objective function as a reference point for analytical and simulation studies[2].

In this approach, energy integration is used in networks to recovery the energy from the hot current, based on the temperature difference compared with the cold current[2], [3]. In this way, it is possible to reduce the production cost, with integration between the hot and cold thermal energies. This can then be used in other networks, to minimize the consumption of energy in the industrial process[2].

The energy optimization technique commonly used is related to pinch technology, proposed in 1979 by LINNHOFF AND BOLAND[4] and the reuse of energy, based on the conservation of energy principles, which are associated with the first law of thermodynamics. The implementation of this procedure enables the structure of networks to be develop using thermal exchange and through energy integration this should result in energy reuse, to minimize the consumption and cost of energy [5].

A key concept of pinch technology analysis is setting energy targets, which is a key part of energy monitoring schemes. The targets are thermodynamic and show that the process is able to recover heat with heating and cooling through the integration of the currents. Pinch technology analysis is based on objective analysis in contrast to other approaches to improvements, which are based on learning curves. It now forms an integral part of the overall strategy for process development and design, often known as process synthesis, and the optimization of existing industrial plants.

Pinch analysis to related to specific techniques, which are key to the design of inherently energy-efficient plants. It was initially implemented with the use of manual analysis but the procedure has increasingly relied on the use of computational tools.

According to Liporace[6], in this progression, specific mathematical algorithms were developed to support different types of analysis[7]. However, high-performance computers allow the use of other energy integration techniques, based on consistent mathematical models [3].

In this context, Flouras et al.[8] performed studies based on non-linear programming networks, for energy optimization. The study was divided into two steps:

i. the first is related to the definition of design goals and determination of the ΔT_{min} gradient, parameters that are used to build the cascade and pinch point;
ii. the second is related to the network synthesis, to find the optimized network, which results in a reduction in several energy and operational costs.

Fig. 1 shows evidence of an overall pinch (ΔT_{min}). Also, it can be observed that if the parameter ΔT_{min} decreases the heat consumption reduces.

The strategies adopted by Flouras et al.[8], according to Stinghen[9] and Grandson[1], allow the rational use of energy, which poses a challenge to the chemical industry and is a decisive factor in the development of any country.

Liporace[10] proposed the retrofit method to optimize the network heat exchangers in order to increase the energy recovery using the maximum number of heat exchangers that are already present, i.e., by adding the minimum new area of thermal exchange.

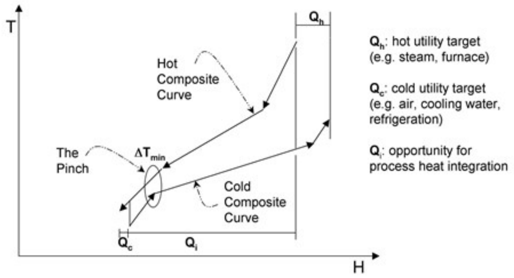


Fig. 1: Strategy used to evaluate and apply the pinch technology[8].

The approach to problems in the retrofit method is the same as that observed in the synthesis of new networks [11]. For this type of analysis, Gadalla et al.[14] applied the pinch technology to oil refinery plants to recover the thermal energy associated with each current present in the crude oil distillation unit using a block diagram, as shown in Fig. 2.

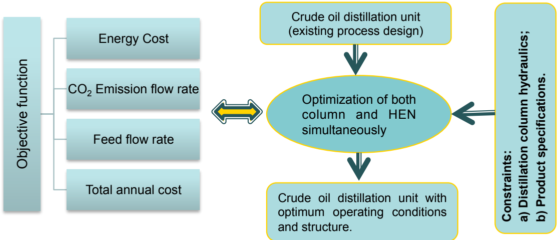


Fig. 2: The main parameters associated with applying the pinch technology (adapted from Gadalla[14])

On the other hand, Fonseca[12] proposed a new network methodology for the heat exchangers used for the pre-heating of crude oil, involving atmospheric and vacuum distillation petroleum refineries, using data from Petrobras[12]. As a result, great potential for the use of this method for industrial energy optimization was observed in terms of cost reductions.

Castro et al.[13] performed a study using a retrofit method for the pre-heating of crude oil in atmospheric and vacuum distillation. The results showed a significant reduction in the thermal consumption for all tests.

Amaral[3] described the energy optimization of distillation units and a furnace, based on pinch methodology, where the technical and economic feasibility of implementing this technology was verified along with its relevance to industrial plants.

Based on all of these concepts, it was possible to evaluate the possibility of using the operational data for a refinery to determine the energy profile, employing a heat exchange network (HEN), in the atmospheric distillation column.

1.1. Refinery Process

The fieldwork was conducted at the Luanda refinery, where data were collected during the operation of the unit. The data were used to evaluate the energy integration using pinch methodology, described above, for the atmospheric distillation unit. The atmospheric distillation unit has 41 trays and its design is shown in Figure 3.

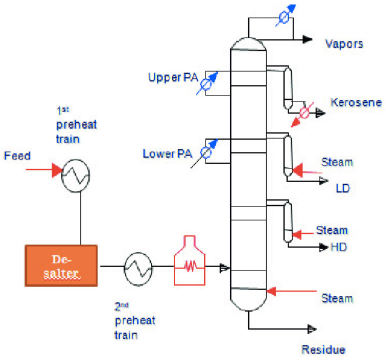


Fig. 3: Schematic diagram of an industrial oil-processing unit[14].

In atmospheric distillation, the desalted crude oil is heated in a heat exchanger and furnace to approximately 416°C and then fed to a vertical distillation column. The vaporized crude oil is separated into various fractions by condensation on 41 trays, each corresponding to a different condensation temperature. Lighter fractions condense and collect toward the top of the column. Heavier fractions, which may not vaporize in the column, undergo further separation in a second column by vacuum distillation.

The atmospheric distillation column used here has four side streams of low-boiling components that are removed from the tower from different trays. The low-boiling-point mixtures are in equilibrium with the heavier fractions, which must be removed. Each side stream is sent to a different small rectification column.

2. Data Collection and Analysis

After the acquisition of the data, the most relevant operational variables of the unit were defined, considering the Luanda refinery design. The data were evaluated for one month and used to close the mass and energy balances. The pinch technology concepts were implemented using a program based on Excel, developed by UFRJ, and the data were validated using the SuperPro Designer Simulator.

The main macroscopic variables studied were pressure, temperature, flow rate and liquid level in the tanks. With the process variables identified, the objective function and its relation with the other variables were established. The thermal energy consumption was defined as the objective function and its relation to each process variable was determined to identify those with most relevance in this process. These relations revealed the interaction between the parameters and allowed the best conditions, aimed at reducing the energy consumption in an atmospheric distillation column, to be defined.

2.1. Description of Heat Exchanger Network

In the synthesis of the heat exchangers, the pinch methodology was divided into two parts:

a) Targeting: Define design goals and propose the heat exchanger network synthesis using the data on the process;

b) Heat exchanger network synthesis: Use the heat exchanger network for integration analysis to minimize the energy cost.

2.2. Energy Analysis

For the energy analysis, the heat exchanger network was developed, with the integration of chains, based on pinch technology principles, supported by data obtained from the atmospheric distillation column at the refinery, to define the energy consumption and equipment cost.

The mass and energy balances were then obtained through pinch technology analysis in spreadsheet software, which enabled the construction of the composite and grand composite curves. The balance allows a cascade of each heat exchanger battery to be obtained for the pinch analysis. After the energy integration, the best heat exchanger network was identified. In this case, 10°C was the temperature gradient selected between hot and cold streams associated with the process, according to Perlingeiro[17]. The heat exchanger network structure and the energy integration enabled the optimization of the heat exchanger network, as described herein. The results of this methodology are shown as the thermal exchange areas and material type used to determine the global heat transfer coefficients for each network.

2.3. Economic Evaluation

After the analysis of the heat exchanger network based on the pinch technology, the financial and economic viability were also evaluated, to establish the investments needed to implement the design. To support this study, the commercial simulator SuperPro Designer was used, with technical limitations due to the absence of flow controllers in the refinery.

3. Results and Discussion

The atmospheric distillation column evaluated was designed to process 4600 ton/d, corresponding to 226.1 m^3/h of crude oil. In this study, the industrial unit used 18% and 82% crude oil from Plutonium and Palanca, respectively, according to Table 1.

Table 1: Mass Balances in Atmospheric Distillation Unit.

Products	Density (kg/m3)	Outflow (m^3/h)	Outflow (ton/d)	%
Crude Oil	0,85	226,10	4605,93	100,00
Naphtha from T-154	0,71	21,82	370,19	8,04
Naphtha from T-151	0,74	21,93	388,48	8,43
Kerosene	0,80	34,00	655,00	14,22
Diesel	0,84	50,99	1035,06	22,47
RAT	0,93	84,18	1877,28	40,75
Total output	----	----	4326,09	93,92
Losses	----	----	279,84	6,08

Table 1 shows the input and output flow rates for this industrial equipment, used to obtain the mass and energy balances. The high temperature and thermal energy of the outflow should be harnessed for the pre-heating of other flows, thus achieving energy reuse. In this way, with the current from the network described in Fig. 2, the crude oil (C.O.) is pre-heated before entering the boiler, using thermal energy from currents 2 (naphta), 6 (kerosene) and 10 (intermediate reflux).

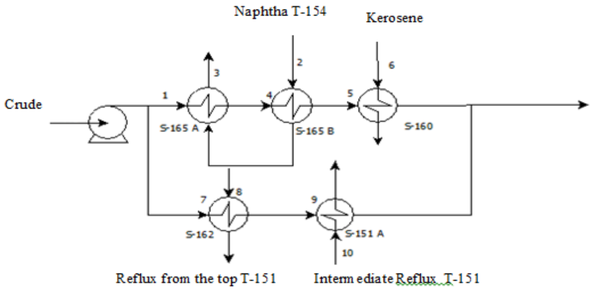


Fig. 4: First heat exchanger battery of Luanda refinery without application of pinch technology.

Figure 4 shows the thermal analysis of the process, based on the pinch technology, supported by the Pinch Analysis Spreadsheet IChemE software and the results from Figure 5a. This procedure uses the data from hot and cold currents, such as the temperature and heat capacity (J/kg.K). These data were used to calculate the enthalpy (ΔH) of the process and a new heat exchanger network was proposed, based on the pinch technology. The results are shown in Table 2.

Table 2: First heat exchanger battery with experimental data.

Stream Name	Supply Temp.	Target Temp.	Mass Flowrate	Specific Heat Capacity	Heat Flow	Stream Type	Supply Shift	Target Shift
	ºC	ºC	Kg/h	J/(kg.K)	KW		ºC	ºC
Cold_1	40,0	62,0	129516,800	1842,0	1457,9274	COLD	45,0	67,0
Hot_2	120,0	102,0	24800,000	2220,0	275,2800	HOT	115,0	97,0
Hot_3	98,0	74,0	24800,000	2220,0	367,0400	HOT	93,0	69,0
Cold_4	62,0	106,0	129516,000	1842,0	2915,0549	COLD	67,0	111,0
Cold_5	94,0	110,0	129516,000	1842,0	1060,3109	COLD	99,0	115,0
Hot_6	177,0	123,0	27295,000	1967,0	805,3390	HOT	172,0	118,0
Cold_7	40,0	80,0	27366,900	1842,0	560,1092	COLD	45,0	85,0
Hot_8	128,0	68,0	44200,000	2220,0	1635,4000	HOT	123,0	63,0
Cold_9	80,0	128,0	27366,900	1842,0	672,1311	COLD	85,0	133,0
Hot_10	222,0	144,0	65650,000	1967,0	2797,8936	HOT	217,0	139,0

3.1. First Battery Synthesis

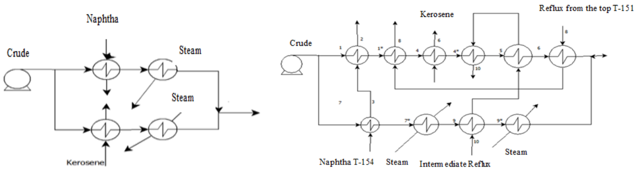
For the new heat exchanger network, another form of interaction between the currents was identified, based on the difference between their temperatures. The proposed configuration could identify the pinch point located above the reference values that requires the new heat exchangers to ensure the optimized conditions for the process.

For this analysis, the association based on the following principles was considered:

a) The number of hot currents must be equal to the number of cold currents;

b) $Cp_q \leq m.Cp_c$, above the pinch point.

The principles described above allowed us to determine the energy needed for the process, which required the insertion between two new energy sources, that is, hot streams with 192.9 KW and 592.4 KW, respectively, resulting in the heat exchanger network configuration shown in Fig. 5.



a) b)

Fig. 5: Network obtained from first battery thermal exchange applying pinch analysis: a) first network found and b) optimized network found.

Fig. 5 shows the first battery used to find two heat exchanger networks: one with a better rationalization of power distribution of the heat exchangers and the other with a heat exchanger network based on pinch technology.

3.2. Second Battery Synthesis

In the synthesis of the second battery of the heat exchanger network a new strategy for the integration of the currents was used, to obtain the best thermal energy associated with each current, as shown in Fig. 6.

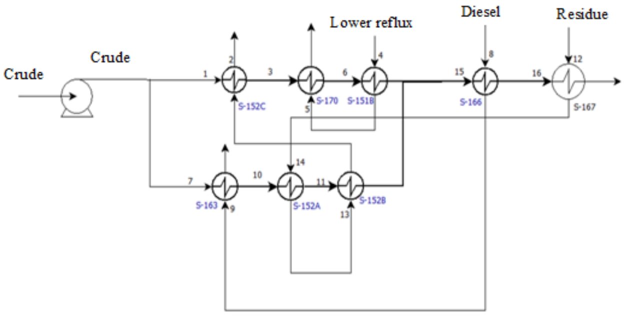


Fig. 6: Second heat exchanger battery without pinch technology: experimental data.

Fig. 7 shows the analysis based on pinch technology, carried out using the same procedures adopted for the first battery, to find the most appropriate configuration with the best efficiency.

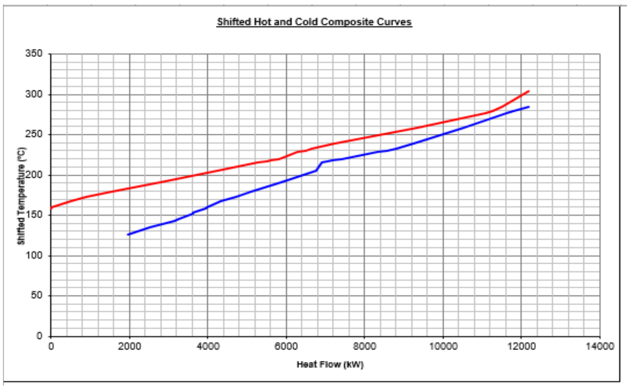


Fig. 7: Second heat exchanger battery without pinch technology: Graph showing hot and cold composite curves.

The composed curve for the second battery shown in Fig. 7 and the temperature and enthalpy of the hot and cold profiles show the approximation points between two currents, respectively, at 309 °C (hot) and 299 °C (cold), called the pinch point.

The pinch point defines the location where there is the least heat transfer intensity in the process. At this point, there is no heat transfer from the hot to the cold current. To increase the heat transfer, it is necessary to use additional heat.

Based on the results reported in Fig. 7, the proposed new heat transfer network to enhance the thermal exchange between currents according to Fig. 8, needs energy integration when the procedure is based on that reported herein. It is evident that when current below the pinch point are present, an increase in the external heat exchangers is required, with the premise:

a) The number of hot currents must be equal to the number of cold streams;

b) $Cp_f \leq m.Cp_h$, below the pinch point.

With this procedure, the new heat exchanger network supplies 1277.1 kW of energy in cold, according to the configuration shown in Fig. 8.

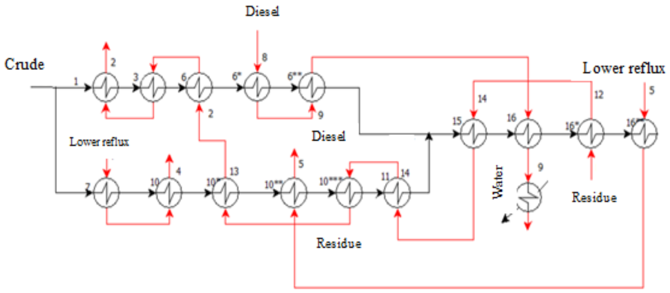


Fig. 8: Heat exchanger network proposed for the second battery: first network found.

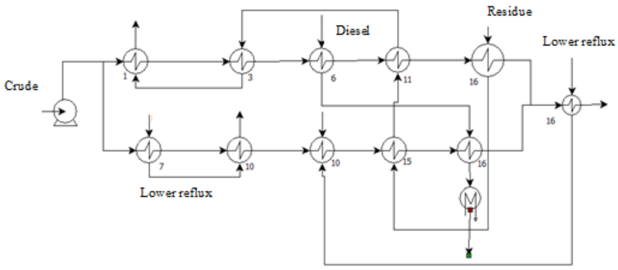


Fig. 9: Heat exchanger network proposed for the second battery: second network found

According to Fig. 9, for the second battery, it was possible to find two new heat exchanger networks, which show better rationalization and power distribution when compared with the pinch point technology.

3.3. Comparison between the networks

With the heat exchanger networks evaluated in this paper, the outlet cold currents conditions were defined. According to Fig 10, the temperature increased from 121°C to 136°C.

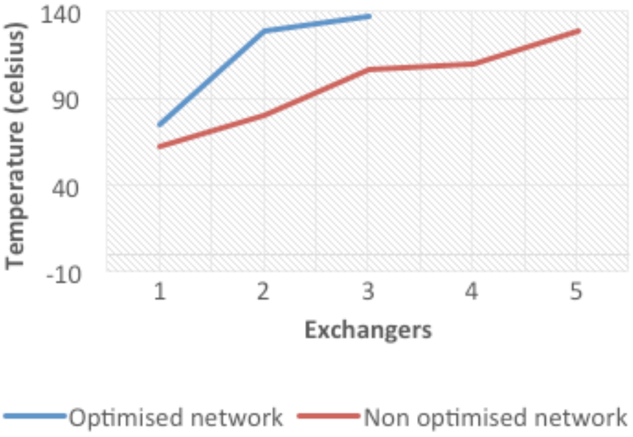


Fig. 10: Comparison of the cold exit temperatures of the first network

The analysis described above shows that the outlet temperature of the cold currents of the second network increase from 280°C to 301°C on comparing the networks (optimized and non-optimized). For the optimized network, the temperature increased with the heat transfer flow rates, due to greater thermal exchange between the currents.

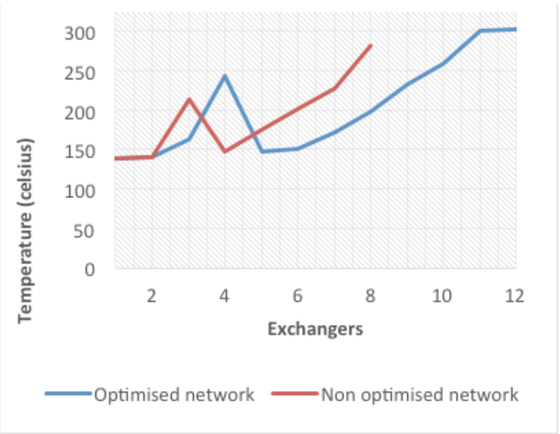


Fig. 11: Comparison of the cold exit temperatures for the second network.

4. Conclusions

Based on the results reported herein, we can conclude the following:

- i The oil industry needs to give more attention to energy use, in order to define the best use of this resource aimed at improving the operational efficiency and performance;
- ii For a better use of energy, integration of the heat exchanger networks is required to optimize the processes, using the best computational tools available;
- iii The energy network integration leads to greater distillation efficiency, mainly at the oil refinery;
- iv The Luanda Refinery should seek to use the integration tools to improve the process efficiency and the financial results;
- v When the heat exchanger networks are used, the cold stream temperature increases due to increased heat transfer;
- vi When the processes are optimized, fuel consumption is reduced;
- vii Pinch analysis is an appropriate tool for energy analysis and to implement heat exchanger networks to optimize the process.

Acknowledgments

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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