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FULL LENGTH ARTICLE

Application of energy management coupled with fuel switching on a hydrotreater unit

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Abstract In the last decades, saving energy and protecting environment became the most important topics for search and survey. The energy engineer for any chemical process is obliged by restrictions of "Kyoto Protocol" for limitation of carbon dioxide emissions from fuel combustion, so he does his best to reduce utility consumption and thus reduce gas emission. Proper designing of the heat exchanger network (HEN) for any process is an effective and successful method to minimize utility consumption and therefore minimize gas emission (mainly carbon gases (CO_2) and sulfur gases (SO_x)). Fuel switching coupled with energy targeting achieved the least gas emission. In this work we choose a hydrotreater unit of a petroleum refinery as a case study due to its effective role and its obvious consumption of utility. We applied the methodology of energy targeting through HEN design (using pinch technology) at several values of mean temperature difference (ΔT_{min}); where the maximum percentage of energy saving was 37% for hot and cold utility which directly leads to percentage reduction of gas emission by 29% for CO_2 and 17% for SO_x. Switching fuel oil to other types of fuel realized gas emission reduction percentage where the maximum reduction established was through natural gas fuel type and reached 54% for CO_2 and 90% for SO_x. Comparison between existing design and the optimum ΔT_{min} HEN led to few modifications with the least added capital cost for the hydrotreater existing design to revamp it through four scenarios; the first one depended on fuel switching to natural gas while the second one switched fuel to diesel oil, in the third scenario we applied heat integration only and the fourth one used both of heat integration and fuel switching in a parallel way.

1. Introduction

The change in the atmospheric air quality is strongly related to the emissions of gases from chemical processes and power generation plants. The combustion of fossil fuel by the chemical process industries and power plants contributes greatly to the emissions of carbon dioxide, as well as nitrogen oxides, sulfur oxides and particulates. The relationship between energy

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Nomenclature

CP	heat capacity flow rate (MJ/h °C)	T_s	supply temperature (°C)
HEN	heat exchanger network	T_{STACK}	stack temperature (°C)
HENS	heat exchanger network synthesis	T_{in}	inlet temperature of stream (°C)
HENs	heat exchanger networks	T_{out}	outlet temperature of stream (°C)
H	heat transfer coefficient (MJ/m^2 °C)	T_{TFT}	theoretical flame temperature (°C)
MER	maximum energy recovery	ΔT_{min}	minimum approach temperature difference (°C)
PDM	the pinch design method	β	mass percentage of the pollutant in non-oxide form (dimensionless)
M_{pol}	mass flow rate of pollutant (kg/h)	ϕ	the ratio of the molar mass of the oxidized form to the non-oxidized form of the pollutant (dimensionless)
NHV	fuel net heating value (kJ/kg)	η_{furn}	furnace efficiency (dimensionless)
Q_{fuel}	heat duty from fuel (kW)		
Q_{proc}	process heat duty (kW)		
T_o	ambient temperature (°C)		

efficiency and flue gas emissions is clear [1]. Many approaches have been proposed to control and/or reduce the greenhouse gas emissions, such as carbon capture, fuel switching, CO_2 storage, and process integration. Among all approaches, improvements in efficient use of energy and changes in fuel selection appear to be most straight forward as well as financially feasible [2]. The more inefficiency in our use of energy, the more fuel we burn and hence the greater are the flue gas emissions [3].

In the past three decades, extensive efforts have been made in the fields of energy integration and energy recovery technologies due to the steadily increasing of energy cost and shortage of energy resources. A heat recovery system consisting of a set of heat exchangers can be treated as a heat exchanger network (HEN), which is widely used in process industries such as gas processing and petrochemical industries [4].

Over the past decade, the pinch analysis technique and mathematical programing approaches have been widely adopted to achieve energy consumption reduction by achieving optimal heat exchanger network (HEN) [2,5]. The most important methods used in designing of HEN are mathematical programing assignment problem methods [6–8] and thermodynamic-based methods [9–15]. Some recent methods have appeared for designing of HEN such as genetic algorithm [16,17], genetic/simulated annealing algorithm [18–21] and tabu search procedure [22].

The pinch design method (PDM) is the most complete thermodynamic method which realized the optimality conditions of the HEN design step by step. It has a track record of worldwide industrial applications that resulted in energy savings of 15–45%. Basics, applications, and benefits of pinch technology are given in Linnhoff et al. [12] see also [http://www.cheresource.com].

The petroleum refining industry uses the largest quantity of premium fuels in the industrial sector. Removal of sulfur is essential for protecting the catalyst in subsequent processes (such as catalytic reforming) and for meeting product specifications for certain "mid-barrel" distillate fuels. Hydrotreating is the most widely used treating process in today's refineries [23]. Hydrotreater unit, removes sulfur, nitrogen and metal contaminants, but it needs about 19% of refinery energy consumption [24]. Improving energy efficiency for this unit is an attractive opportunity for cost and gas emission reductions [25].

In this work, application of energy management by designing the maximum energy recovery (MER) heat exchanger network of a hydrotreater unit coupled with fuel switching can

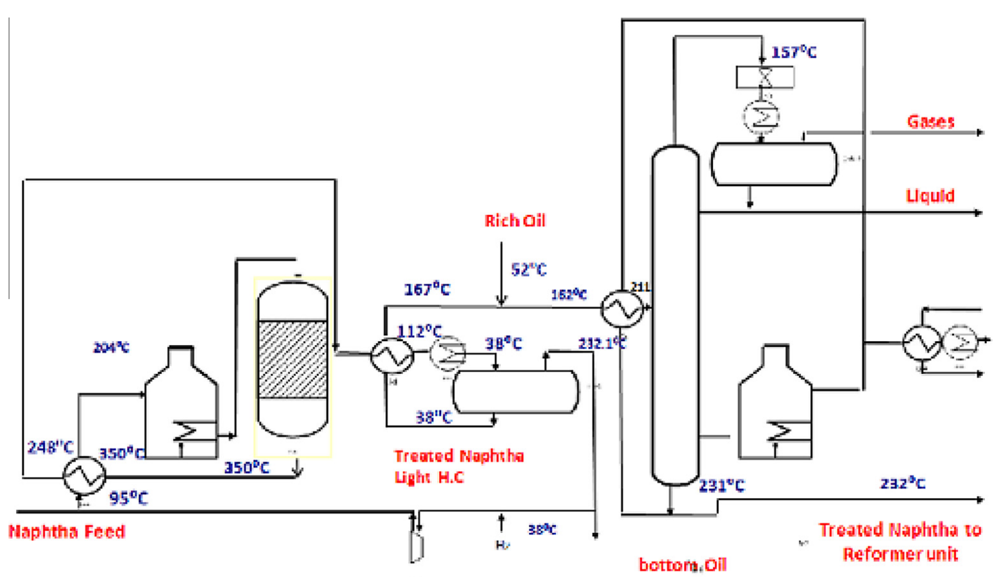

Figure 1 Flowsheet of the existing hydrotreater unit.

realize the least consumption of utility and the least gas emissions.

2. Emissions

Human activities are major contributors to the increase of greenhouse gas concentration in the upper atmosphere, which catalyze global warming effect and lead to melting of polar ice caps, rising sea level, desertification, and weather disruption. Greenhouse gases are defined as gases that are capable of trapping radiative energy emitted by sun [2]. Conventional fossil fuels such as coal, oil and natural gas continue to be a dominant source of primary energy in world economy [26]. The common components of fossil fuels are carbon, hydrogen, sulfur and nitrogen, which, upon combustion with air produce the desired amount of heat required by the process. The combustion reactions are also associated with the emission of harmful pollutants [1,27]. Combustion processes work with excess air to ensure complete combustion of the fuel. The theoretical flame temperature provides an appropriate reference to indicate the maximum amount of heat released by combustion as the flue gas is cooled from the flame temperature (T_{TFT}) to the stack temperature (T_{STACK}). Theoretical flame temperature of the flue gases are usually in the region of 1800 °C. Stack temperature should not be lower than the corrosion limit. A typical stack temperature of 160 °C is adopted. The furnace efficiency is defined as the ratio of the useful heat delivered to the process to the amount of fuel burnt [1]. The heat duty from fuel and targeting the emission rate of various pollutants for a given fuel can be estimated through Eq. (1)–(3) [28]

$$\eta_{furn} = \frac{T_{TFT} - T_{STACK}}{T_{TFT} - T_o} \tag{1}$$

$$Q_{fuel} = \frac{Q_{proc}}{\eta_{furn}} \tag{2}$$

$$M_{pol} = \frac{Q_{fuel}}{\mathrm{NHV}} \beta\phi \tag{3}$$

where:
η_{furn}: the furnace efficiency (dimensionless),
T_{TFT}: the theoretical flame temperature °C,
T_{STACK}: the stack temperature °C,
T_o: the ambient temperature °C,
Q_{fuel}: heat duty from fuel,
Q_{proc}: the process heat duty,
M_{pol}: the mass flow rate of pollutant,
NHV: the fuel net heating value,
β: the mass percentage of the pollutant in non-oxide form,
ϕ: the ratio of the molar mass of the oxidized form to the non-oxidized form of the pollutant.

Table 1 Streams' specification of the case study.

Stream	Inlet temperature (T_{in}) °C	Outlet temperature (T_{out}) °C	CP MJ/h °C	H MJ/m^2 °C
Reactor effluent (h1)	350	38	165.6	2.02
Lean oil (h2)	232	38	13.5	1.7
Stripper condenser (h3)	157	38	273.9	2.02
Reactor feed (C1)	95	350	167.3	2.02
Stripper feed (C2)	38	167	117.8	2.02
Stripper feed 2 (C3)	52	130	12.0	2.02
Mixed stripper feed (C4)	162	211	212.6	2.02
Stripper reboiler (C5)	231.9	232	249690.0	2.02

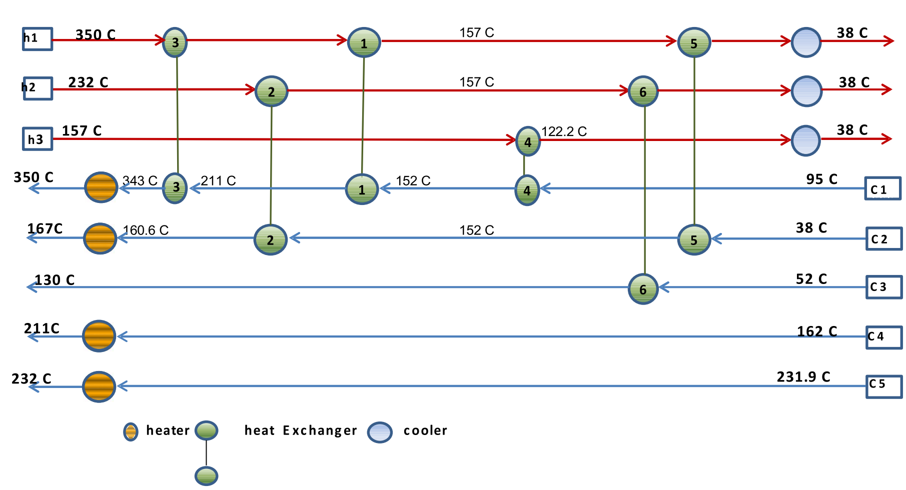

Figure 2 Heat exchanger network of the case study at ΔT_{min} of 5 °C.

3. Hydrotreater unit as a case study

The function of this unit is removing sulfur compounds from naphtha by catalytic hydrotreating. This step is necessary to protect the valuable reforming catalyst from poisoning due to the presence of sulfur compounds in naphtha feed.

3.1. Process description

The flowsheet of the hydrotreater process unit is shown in Fig. 1. Naphtha feed is mixed with the recycled hydrogen and preheated against the hot reactor effluent product to a temperature of 204 °C. The mixed feed is then heated in a fired

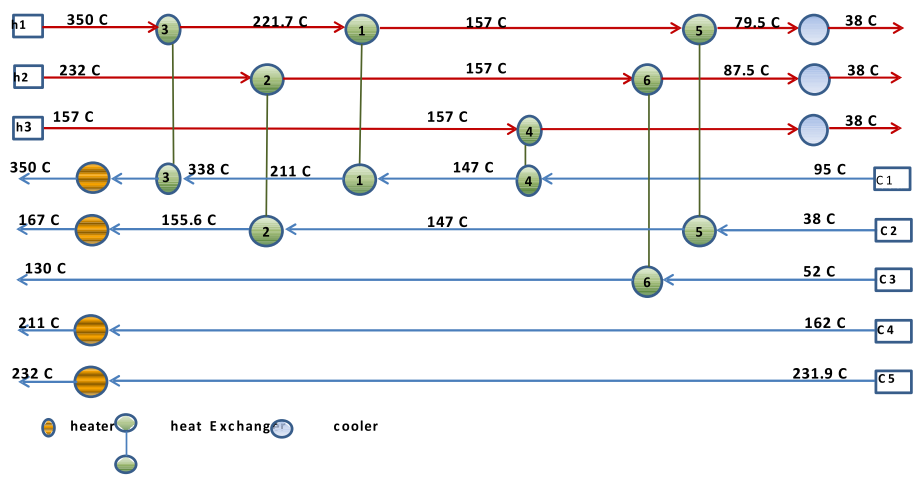

Figure 3 Heat exchanger network of the case study at ΔT_{min} of 10 °C.

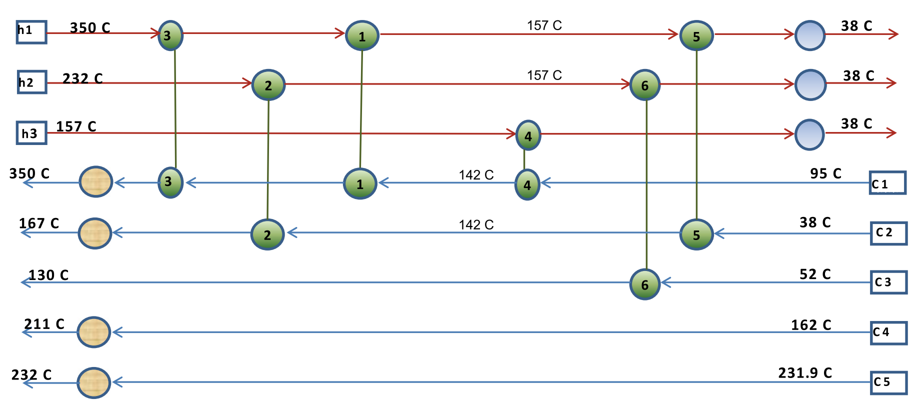

Figure 4 Heat exchanger network of the case study at ΔT_{min} of 15 °C.

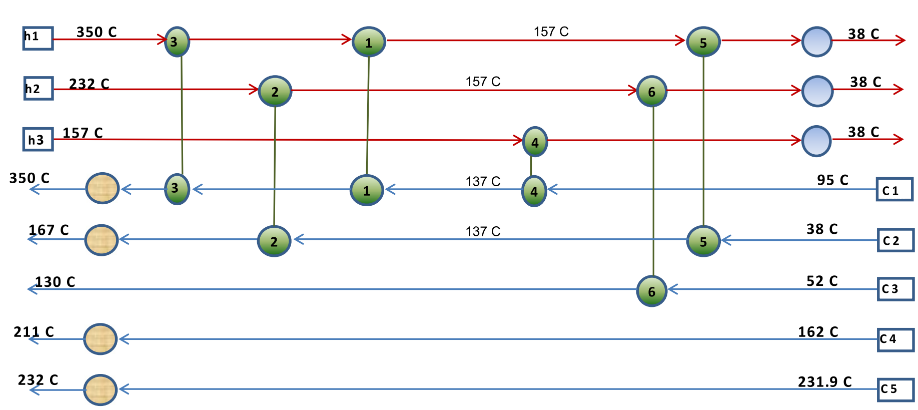

Figure 5 Heat exchanger network of the case study at ΔT_{min} of 20 °C.

heater to a 350 °C and introduced to the top of the fixed bed reactor. The reactor condition is adjusted to keep the reactor temperature at 350 °C although the reaction is exothermic. The reactor effluent exchanged heat with the reactor feed firstly then with the stripper feed and finally cooled to a temperature of 38 °C. The reactor effluent is then separated into vapor and liquid fractions. The vapor contains mainly hydrogen which is recycled to the feed stream, while the liquid fraction is a mixture of the treated naphtha and some light hydrocarbons which must be stripped off before transferring the treated naphtha to the reformer unit.

Using data sheet of input stream chemical analysis, operating condition, product specifications and process simulation program to calculate mass and energy balance and estimate the intermediate streams properties, the actual consumption of energy for the hydrotreater unit can be calculated as 54803.1 MJ/h and 47266.8 MJ/h for hot and cold utilities, respectively.

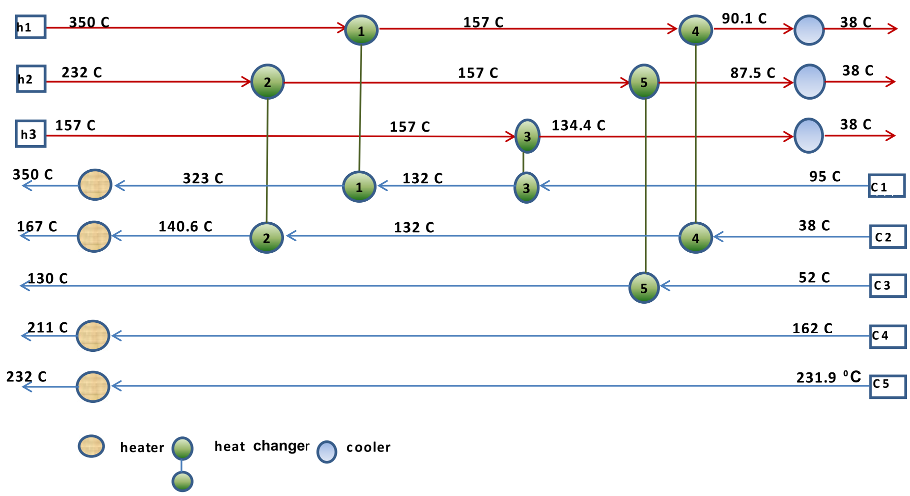

Figure 6 Heat exchanger network of the case study at ΔT_{min} of 25 °C.

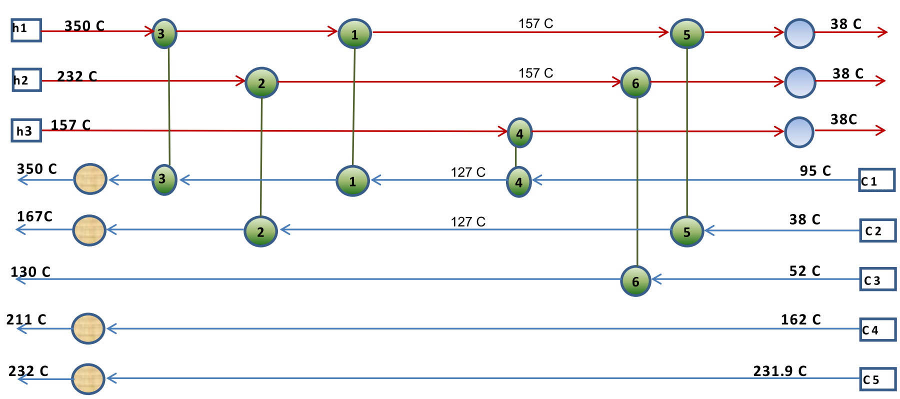

Figure 7 Heat exchanger network of the case study at ΔT_{min} of 30 °C.

Table 2 Summary of the hydrotreater HENs' specification at different values of ΔT_{min}.

ΔT_{min} °C	Hot utility consumption MJ/h	Cold utility consumption MJ/h	% Saving of hot utility	% Saving of cold utility	Capital cost of HEN $/y	Overall annual cost $/y	№ of units	Pinch Pt °C	% Gas emission reduction as a result of energy management	
									% CO_2 reduction	% So_x reduction
5	37308.3	29999.8	32	36.5	226,269	3,271,528	13	154.5	29	17.3
10	38733.8	31425.6	29	33.5	175,249	3,337,407	13	152	26.7	14.1
15	40159.3	32850.8	27	30.5	134,715	3,413,772	13	149.5	24	10.8
20	41584.8	34276.2	24	27.5	110,956	3,506,910	13	147	21.3	7.6
25	43010.3	35701.7	21.5	24.5	87,228	3,600,081	12	144.5	18.6	4.5
30	44471.8	37163.2	19	21.4	76,066	3,708,769	13	142	15.8	1.3

3.2. Energy targeting through heat exchanger network synthesis (HENS)

Minimizing the hydrotreater utilities can be realized by applying pinch technology to design HEN. The first step was classification of the process streams into hot and cold streams with their specifications as shown in Table 1. Due to the effect of minimum approach temperature difference (ΔT_{min}) on both capital and operating costs, determination of minimum consumption of utilities at several values of (ΔT_{min}; 5, 10, 15, 20, 25, 30 °C) took place as the second step. By applying pinch technology technique, we designed a HEN for the hydrotreater unit at each value of ΔT_{min} (see Figs. 2–7). Energy target through designing of HENs realized minimizing of heavy fuel oil consumption as a hot utility (reached to 32%) and thus reduction of gas emissions (reached to 29% of CO_2 and 17% of SO_x) as shown in Table 2. (Properties and prices of fuel types are presented in Table 3). The rate of fuel emissions is computed by applying Eq. (1)–(3) [28].

3.3. Combined process integration and fuel switching strategy

Fuel switching from heavy fuel oil into natural gas, diesel oil and coal took place, where the rate of gas emissions for each fuel is computed by applying Eq. (1)–(3) and using alternative fuel analysis [28]. The effect of fuel type and its emission on every HEN for the hydrotreater unit is shown obviously in Table 4. According to the fuel type the least emission is accomplished with natural gas while the use of coal led to much emission as shown in Table 4. Economic analysis among several scenarios should take place to choose optimum conditions of HEN design and fuel type.

Table 3 Classification and properties of different types of fuels.

	Natural gas	Diesel oil	Fuel oil	Coal
NHV (MJ/kg)	51.2	42.0	39.57	30.0
Cost ($/GJ)	4.21	7.79	9.9	1.61

3.4. Economic analysis and cost targeting

We have several designs of HEN for the hydrotreater unit as shown in Figs. 2–7, we must estimate the overall cost to compare between them taking into consideration gas emission [1,29]

$$\text{Overall Annual Cost} = \text{Annualized Operating Cost (OC)} + \text{Annualized Capital Cost (CC)} \tag{4}$$

$$\text{Annualized Operating Cost (OC)} = \text{Fuel cost} + \text{Cold Water Cost} \tag{5}$$

$$\text{Annualized Capital Cost (CC)} = \text{Capital Cost of HEN} \tag{6}$$

$$\text{Exchanger Capital Cost (\$)} = 8600 + 670\ (\text{area})^{0.83} \tag{7}$$

$$\text{Life time} = 5\ \text{years} \qquad \text{No. of working days/y} = 330 \tag{8}$$

Operating cost, capital cost and thus the overall annual cost of every HEN design were estimated for the three types of fuel (natural gas, diesel oil and coal).

Table 5 is a collection of options for the hydrotreater HEN designs at different values of ΔT_{min} with different types of fuel. According to cost only; coal as a fuel type realized least overall

Table 4 Rate of the fuel gas emissions for the hydrotreater HENs at different values of ΔT_{min} with different types of fuel.

ΔT_{min} °C	Hot utility consumption MJ/h	Cold utility consumption MJ/h	No of units	Pinch Pt °C	Natural gas		Diesel oil		Coal	
					C Emiss. kg/h	S Emiss. kg/h	C Emiss. kg/h	S Emiss. kg/h	C Emiss. kg/h	S Emiss. kg/h
5	37308.3	29999.8	13	154.5	2090.5	2.25	3108.0	15.17	5301.5	121.66
10	38733.8	31425.6	13	152	2170.4	2.33	3226.8	15.75	5504.1	126.3
15	40159.3	32850.8	13	149.5	2250.3	2.4	3345.6	16.32	5706.7	131
20	41584.8	34276.2	13	147	2330.1	2.6	3464.3	16.91	5909.3	135.6
25	43010.3	35701.7	12	144.5	2410.0	2.7	3583.1	17.5	6111.8	140.3
30	44471.8	37163.2	12	142	2491.9	2.8	3704.8	18.08	6319.5	145.0

Table 5 Effect of fuel type on annualized total cost and % gas emission reduction of the hydrotreater HENs at several ΔT_{min}.

ΔT_{min} °C	% Gas emission reduction due to energy targeting						Overall Annual cost $/y according to fuel type		
	Natural gas		Diesel oil		Coal				
	CO_2 (%)	SO_x (%)	CO_2 (%)	SO_x (%)	CO_2 (%)	SO_x (%)	Natural gas	Diesel oil	Coal
5	54	90	32	32	−16	−446	1,528,579	2,586,404	760,327
10	52.5	89.5	29	29.4	−20	−466	1,528,863	2,626,106	730,256
15	50.7	89.2	26.7	26.8	−25	−487	1,537,632	2,676,295	710,672
20	48.9	88.3	24.1	24.2	−29	−508	1,564,174	2,743,256	707,861
25	47	87.9	21.5	21.5	−34	−529	1,590,749	2,810,249	705,082
30	45	87.5	18.9	18.9	−38	−550	1,631,160	2,892,098	712,397

cost but calculation of gas emission reduction indicated that natural gas is the best. The energy engineer can choose one of these options as a new design for the hydrotreater unit depending on the economical conditions of his region.

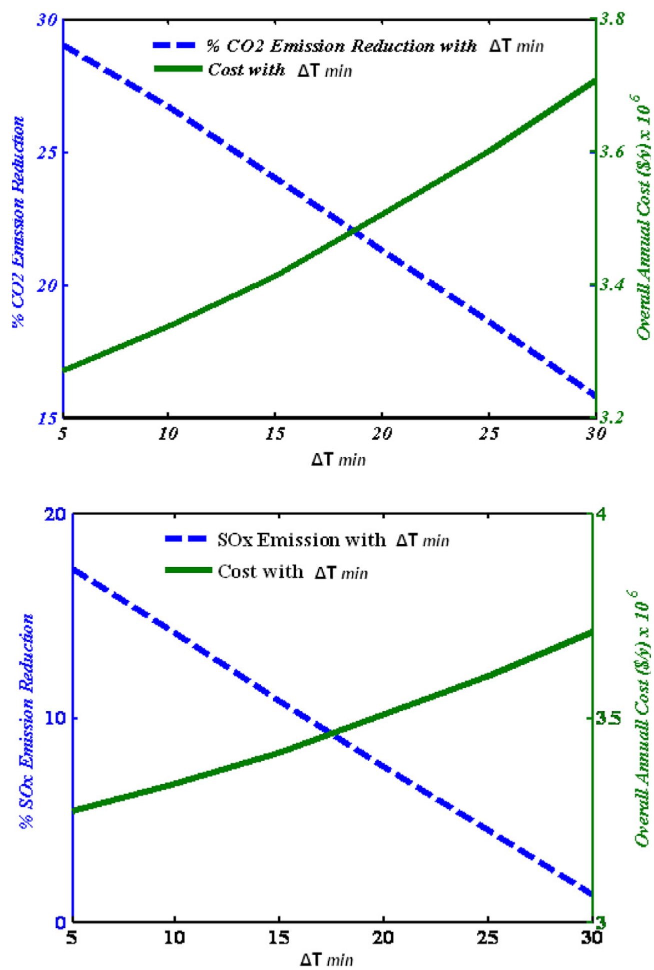

Figure 8 Relation between $\Delta T_{\min}$, overall cost and % gas emission reduction for the hydrotreater HENs using fuel oil.

3.5. Revamping of the existing design of the case study

Table 2 shows that as $\Delta T_{\min}$ increased, minimum hot utility consumption increased so overall cost increased while gas emission reduction percentage is decreased. To choose an optimum value of $\Delta T_{\min}$ for the case study, we plot a curve representing $\Delta T_{\min}$, overall cost and percentage of gas emission reduction [29,30] where the optimum $\Delta T_{\min}$ for the case study is deduced as18 °C; see Fig. 8. The design of the hydrotreater HEN at the optimum $\Delta T_{\min}$ of 18 °C is presented in Fig. 9. The existing HEN of the hydrotreater is presented in Fig. 10. By comparing Figs. 9 and 10 we deduced some required modification for the existing HEN, which are adding the heat exchanger (NO 4) on naphtha feed stream and a heater for cold stream C4 (treated naphtha + light hydrocarbon). The revamped flow sheet is shown in Fig. 11, where the background of the added units are presented in gray color.

Revamping can happen through four suggested scenarios:

The first one is revamping through fuel switching from fuel oil to natural gas where utility consumption of this scenario and existing design are equal while gas emission reduction reached to 35% and 87.8% for both CO_2 and SO_x, respectively and net annual saving is 2,782,894 $/y.

The second is switching fuel oil to diesel oil, so consumption of utilities is similar to the existing but gas emission reduction reached to 28% and 38.7% for both CO_2 and SO_x, respectively and net annual saving is 1,093,909 $/y.

The third scenario depended on heat integration only and the proposed design achieved saving of hot and cold utilities as 25.4% and 28.7%, respectively and accomplished gas emission reduction of 19% with net annual saving as 1,189,981 $/y.

The fourth scenario combined both heat integration and fuel switching and the revamped design achieved the same percentage of utility saving as the third scenario but the gas emission reduction reached to 40% and 88.8% for both CO_2 and SO_x, respectively (when fuel switched from fuel oil to natural gas) and the net annual saving was 3,265,021 $/y.

A summary of the revamped designs' results is shown in Table 6; the four cases achieved improvement in energy saving, gas emission reduction and less operating cost compared to the base case (existing design). While the best case was through heat integration coupled with fuel switching to natural gas

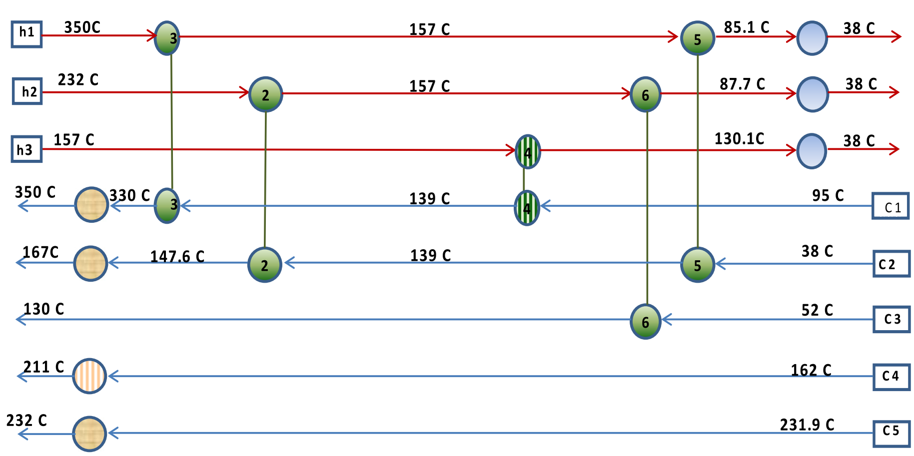

Figure 9 The hydrotreater HEN as $\Delta T_{\min}$ of 18 °C.

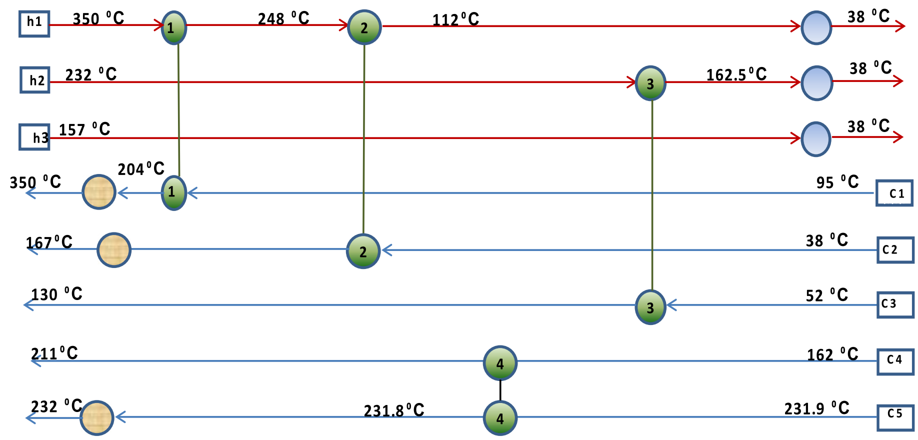

Figure 10 The HEN of the existing hydrotreater.

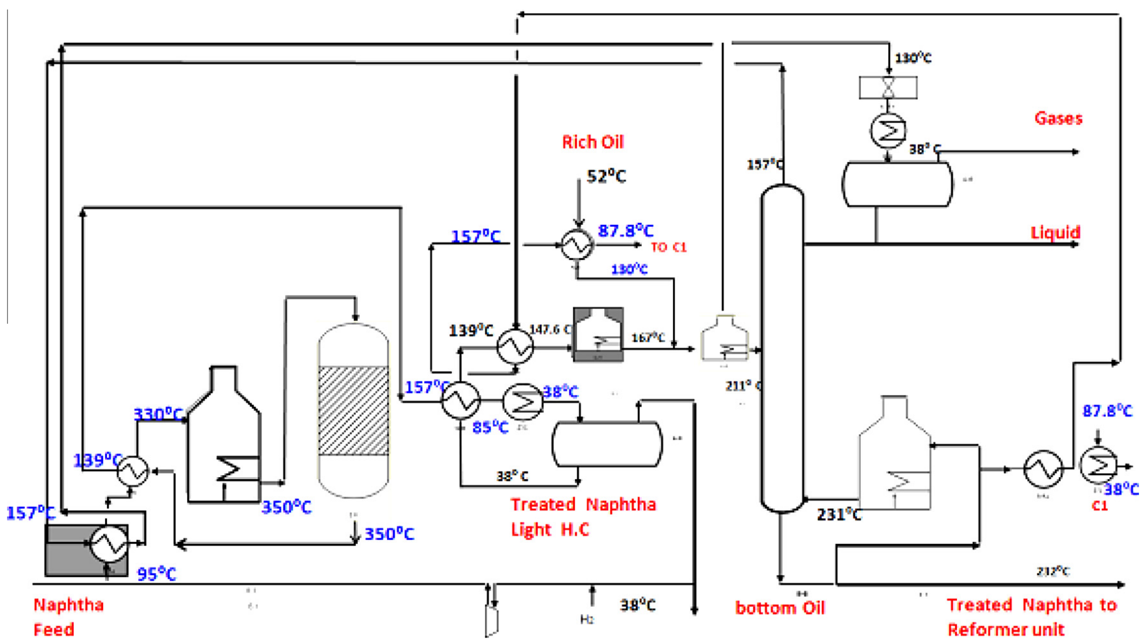

Figure 11 The revamped flow sheet of the hydrotreater unit.

Table 6 Summary of the revamped designs' results for the hydrotreater unit.

Design case	% Saving of hot utility	% Saving of cold utility	Operating cost $/y	Added capital cost $/y	Net annual saving $/y	% CO_2 emission reduction	% SO_x emission reduction
[a]Base case	–	–	4,861,009	–	–	–	–
[b]Case 1	–	–	2,078,115	–	2,782,894	35	87.8
[c]Case 2	–	–	3,767,100	–	1,093,909	28	38.7
[d]Case 3	25.4	28.7	3,621,589	49,439	1,189,981	19	19
[e]Case 4	25.4	28.7	1,546,549	49,439	3,265,021	40	88.8

[a] Base case: existing design using fuel oil.
[b] Case 1: fuel switching from fuel oil to natural gas.
[c] Case 2: fuel switching from fuel oil to diesel oil.
[d] Case 3: heat integration without fuel switching.
[e] Case 4: heat integration with fuel switching to natural gas.

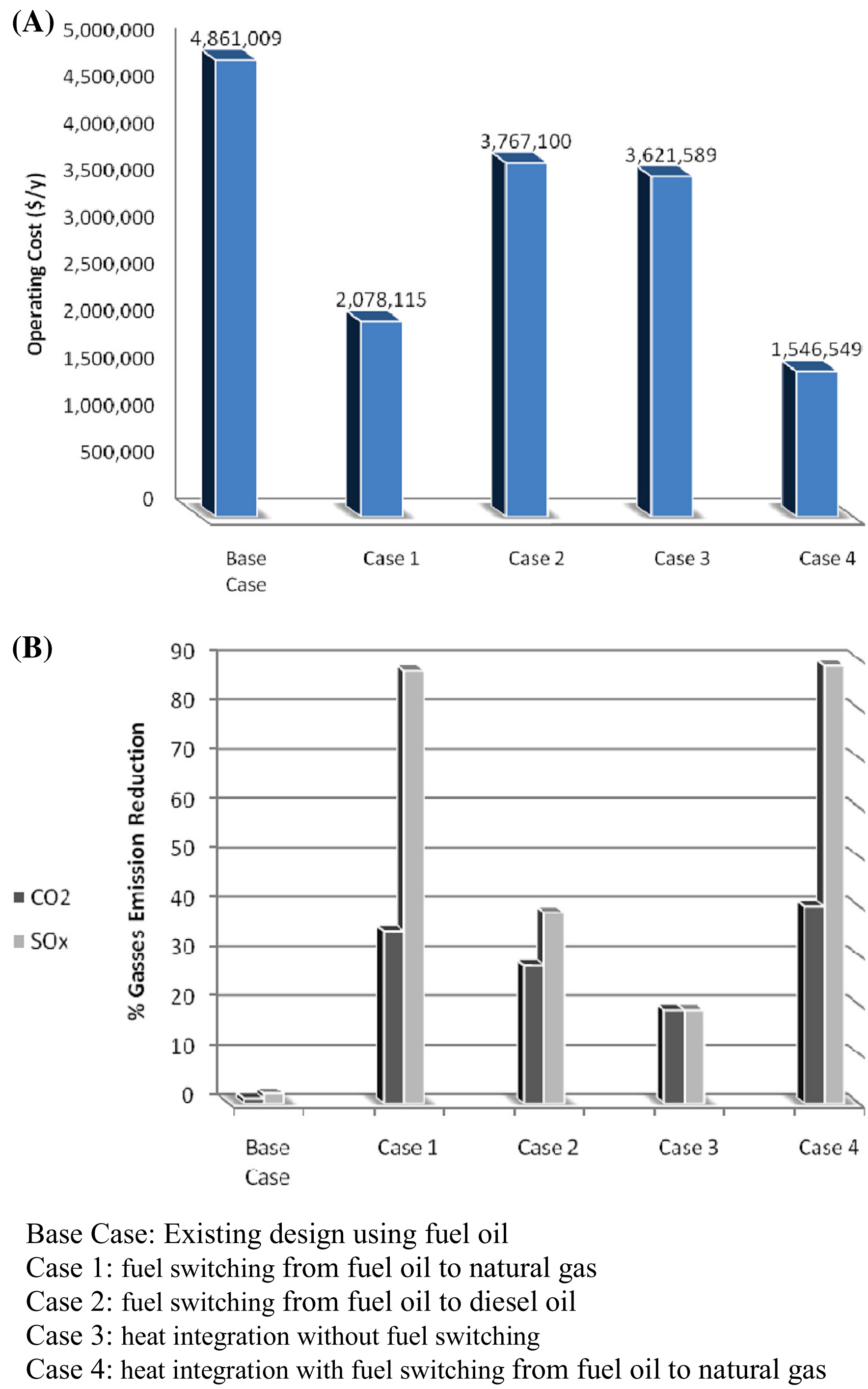

Figure 12 Comparison between base case and the four revamped design cases. (A) According to operating cost and (B) according to % gass emission reduction.

(case 4). Comparison among base case and the four other cases with respect to operating cost and % gas emission reduction is shown in Fig. 12(A) and (B).

4. Conclusion

The pivot of minimizing both of energy consumption and gas emission for any chemical process is realized through MER heat exchanger network synthesis coupled with fuel switching. This methodology was applied on a case study which is a hydrotreater unit of petroleum refinery where results realized as energy saving of 37% for hot and cold utilities and gas emission reduction of 54% for CO_2 and 90% for SO_x. Revamping the existing design of the hydrotreater unit was studied through four scenarios, the four alternative designs realized better results of energy saving, gas emission reduction and net annual saving compared to the existing hydrotreater unit.

Maximum energy saving, maximum gas emission reduction and maximum net annual saving were realized through heat exchanger network synthesis coupled with fuel switching from fuel oil to natural gas. The revamped design in this case achieved saving of hot and cold utilities as 25.4% and 28.7%, respectively, the gas emission reduction reached 40% and 88.8% for both CO_2 and SO_x, respectively and the net annual saving was 3,265,021 $/y.

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