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Enhanced Energy Performance in Refinery Units: The Role of Light Naphtha Fuel Substitution

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ABSTRACT

Enhancement of energy efficiency in refining units that deal with petroleum is one of the major goals in ensuring that the operations are sustainable and environmentally responsible. The research is intended to assess the alternatives between heavy and light naphtha as the furnace feed in refinery units, including the improvements in the energy performance and reduction of emissions. The methodology entails a thorough evaluation that incorporates combustion performance analysis, economic evaluation, and environmental impact assessment, which is based on operational data of the Najaf Refinery. The findings show that replacing light naphtha with light combustion results in enhanced combustion performance, as it contains less carbon and has better fuel characteristics with a significant decrease in carbon dioxide emissions. Moreover, the economic analysis demonstrates the presence of significant cost savings that are related to fuel consumption and operational efficiency, which proves the economic viability of the suggested substitution. Implementation-related technical issues are also determined, and suitable mitigation measures are suggested to facilitate stable and safe operation. In sum, the results support the conclusion that the extensive use of light naphtha instead of heavy naphtha is a viable strategy to increase energy efficiency and decrease the environmental risks at the same time, thus facilitating sustainable refinery processes.

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تحسين الأداء الطاقي في وحدات التكرير: دور إحلال وقود النفثا الخفيفة

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الملخص

يُعدّ تحسين كفاءة استخدام الطاقة في وحدات التكرير النفطية من الركائز الأساسية لتحقيق الاستدامة التشغيلية والحد من التأثيرات البيئية السلبية للصناعات التكريرية. تهدف هذه الدراسة إلى تقييم جدوى إحلال النفثا الخفيفة محل النفثا الثقيلة عند استخدامها كوقود للأفران في وحدات التكرير، مع التركيز على انعكاسات هذا الإحلال على الأداء الطاقي، والانبعاثات الغازية، والجوانب الاقتصادية. اعتمدت منهجية البحث على تحليل متكامل شمل تقييم أداء الاحتراق، والتحليل الاقتصادي، ودراسة الأثر البيئي، استنادًا إلى بيانات تشغيلية فعلية تم الحصول عليها من مصفى النجف. أظهرت النتائج أن استخدام النفثا الخفيفة كوقود بديل يؤدي إلى تحسن ملحوظ في كفاءة الاحتراق، ويُعزى ذلك إلى انخفاض محتواها الكربوني وتحسن خصائصها الفيزيائية والكيميائية مقارنةً بالنفثا الثقيلة، مما أسهم في تقليل انبعاثات ثاني أكسيد الكربون بصورة واضحة. كما أظهرت نتائج التحليل الاقتصادي تحقيق وفورات مالية ملموسة ناتجة عن خفض استهلاك الوقود وتحسين الكفاءة التشغيلية، الأمر الذي يؤكد الجدوى الاقتصادية لخيار الإحلال المقترح. إضافةً إلى ذلك، تم تحديد التحديات التقنية المرتبطة بتطبيق هذا الخيار، واقتراح حلول وإجراءات تخفيفية مناسبة تضمن استقرار التشغيل وسلامته ضمن الظروف التشغيلية للمصفى. وبناءً على ما تقدم، تؤكد نتائج هذه الدراسة أن الإحلال المنهجي للنفثا الخفيفة بدلاً من النفثا الثقيلة يُعد استراتيجية فعّالة لتعزيز كفاءة الطاقة وتقليل الأثر البيئي في آنٍ واحد، مما يسهم في دعم استدامة عمليات التكرير النفطي وتحسين أدائها على المدى الطويل.

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Introduction

The petroleum refining sector is highly important in converting crude oil into transportation fuels and petrochemical feedstocks, as well as experiencing increased demand to enhance energy efficiency and minimize environmental impacts. Refining processes are based on processes that are highly energy-intensive, such as atmospheric and vacuum distillation, catalytic cracking, reforming, and hydrotreatment, which contribute a significant fraction of industrial energy use. In turn, the energy consumption is a significant part of the refinery operating costs, and enhancement of the efficiency is one of the primary economic priorities(Ma et al., 2023; Morrow et al., 2015; Oliveira et al., 2023; Zhao et al., 2021). Simultaneously, rising world alarm on climate change has heightened the regulatory as well as societal pressures to limit the emission of greenhouse gases, resulting in petroleum refining processes (Shui et al., 2024; S. Zhao et al., 2024). Recent research has emphasized a high contribution of the refining industry to global carbon emissions, and substantial differences between countries, businesses, and refinery designs(Ma et al., 2023). Consequently, the enhancement of energy efficiency and reduction of emissions have turned out to be the key

goals of sustainable refinery operation. To attain these objectives, a number of measures have been put forward, such as optimization of operations, benchmarking and efficiency analysis, integration of processes, equipment update, and switching of fuel (Oliveira et al., 2023; Zhao et al., 2021). The fuel switching technique has been one of such strategies that has gained specific focus because it has relatively low capital needs and an immediate effect on combustion efficiency and emissions. The refineries typically utilize heavy naphtha as a fuel in a furnace, but due to its higher boiling range and carbon content, it needs more power to be vaporized and combusted, resulting in increased fuel usage and pollutant generation. Light naphtha, on the contrary, has better volatility and clean combustion properties that may result in a higher thermal efficiency and lower emissions when being used as a furnace fuel(Jo et al., 2024; Ngoma & André, 2023). Experimental and industrial research has shown that naphtha and other low-grade fuels can be used in combustion systems, which are good as they can be used to enhance the performance of combustion in the right operating conditions(Jo et al., 2024; Park et al., 2020). Fuel switching in industrial combustion has been known to have environmental and economic advantages. Indicatively, the use of cleaner fuels (as opposed to heavy fuel oil) has been demonstrated to make a substantial cut in carbon dioxide, methane, nitrous oxide, and sulfur oxide emissions, and has also increased thermal efficiency and cut down the cost of operation (Koumi et al., 2022; Ngoma & André, 2023). Moreover, refinery furnaces have also improved the environmental performance through the increased development of the burner design and combustion control in order to lower the emission of nitrogen oxides and enhance flame stability(Erenkov & Katin, 2020). The research on the behavior of naphtha, evaporation losses, and thermal decomposition gives further understanding of its use in optimized refinery energy usage (Kosachev, Borisov, Yakubova, Mironov, & Yakubov, 2018; Paz et al., 2022). Though progress has been made, the dominant theme of most available studies has been on gaseous fuels, blended fuels, or significant equipment changes, with relatively little consideration on liquid-to-liquid fuel replacement in the refinery furnaces. Specifically, the replacement of the heavy naphtha with the light naphtha as an internal refinery fuel is an unexplored area in terms of integrated technical, economic and environmental considerations. Furthermore, the refinery-specific issues regarding the combustion behavior, furnace operation, and cost effectiveness need to be investigated further to assist in industrial application. Hence, the originality of the current research work is in offering a thorough evaluation of the replacement of heavy naphtha by light naphtha as furnace fuel in the refinery processes. This is based on data obtained using operations at the Najaf Refinery, which assesses the efficacy of combustion, the potential of the reduction of emissions, the economic viability, and the difficulties of implementation, and suggests effective solutions to minimize the problem. This research addresses a poorly studied liquid-to-liquid fuel switching pathway, which, in turn, helps develop cost-effective and sustainable energy optimization strategies at contemporary petroleum refineries and offers practical advice to the refinery operators, process engineers, and policymakers.

Materials and Methods

Study Site and Refinery Processes

This paper explores the improvement of energy efficiency in fuel replacement in the Najaf Refinery, Iraq. The refinery can process about 70,000 barrels of crude oil per day, and it contains large process units, which include crude oil distillation and downstream manufacturing of transportation fuels like gasoline and diesel. The size and nature of the Najaf Refinery offer an appropriate and reflective industrial example of analyzing the potential of fuel substitution strategies to enhance energy efficiency in refinery operations.

Fuel Substitution Experiment

In the context of this study, optimization of energy is achieved by replacing heavy naphtha with light naphtha as the fuel furnace in the units of the refinery process. The study was carried out in a systematic methodological framework that started by conducting a thorough feasibility study to examine the technical and economic climate of the intended substitution. This evaluation took into account the physicochemical characteristics of the fuels, the availability of the latter in refinery processes, and the possible effects on the furnace performance and stability in the furnace operations. Then, a controlled trial operation was introduced whereby a fraction of heavy naphtha was substituted by light naphtha, and key performance indicators such as the energy consumption and atmospheric emissions were monitored continuously. Lastly, the performance analysis was conducted through comparison of the operational data before fuel substitution and subsequent fuel substitution, specifically, energy efficiency, furnace stability, fuel consumption, and environmental emissions, which allowed conducting a quantitative analysis of the efficacy of the light naphtha as an alternative furnace fuel.

Data Collection and Analysis

The study assumed an interdisciplinary method to use both quantitative and qualitative methods of data collection in order to determine the effects of fuel substitution on energy efficiency and operational performance within the refinery. The quantitative data involved in the energy consumption, such as the fuel consumption, important process parameters, like temperature, pressure, and flow rates, and product quality indicators, were taken and evaluated to determine the change in energy efficiency and operational performance following the fuel replacement. Simultaneously, the qualitative data were collected by observing refinery processes and fuel handling activities directly and organizing the interaction with refinery workers to record their views and operational experience related to the implementation of the fuel substitution strategy.

Fuel Characterization

A physical and chemical analysis of the heavy and light naphthas fractions was conducted to determine their appropriateness to be used as furnace fuels. The light naphtha fraction, as shown in Table 1, has a lower specific gravity and, therefore, higher API gravity than heavy naphtha, meaning that it is less dense(Paz et al., 2022). Moreover, light naphtha is also defined by a lower initial boiling point, which means a higher content of the lighter hydrocarbon components and higher volatility(Kosachev et al., 2018). Such properties are advantageous to its quick evaporation, and its uses are especially appropriate in processes that need quick combustion, e.g., catalytic reforming and gasoline blending. Comparatively, heavy naphtha is mainly composed of higher molecular weight and boiling point hydrocarbons(Park et al., 2020). It has a greater specific gravity and lower API gravity, which signifies its heavier composition compared to light naphtha (Nelson et al., 2019) . Moreover, the distillation profile of heavy naphtha has a higher starting point of boiling and a smoother distillation curve, which confirms the existence of a higher proportion of heavier hydrocarbons. Due to these properties, heavy naphtha is usually used in processes like steam cracking to make olefins or used as feedstock in making aromatics (Rahim et al., 2019; Shafei et al., 2022).

Table 1: shows typical analyses of light and heavy naphtha from two different kinds of crude oil at the Najaf refinery

Test Type	Light Naphtha		Heavy Naphtha	
	Second Sample	First Sample	First Sample	First Sample
SP crude oil	0.88112	0.88883	0.8811	0.8888
API crude oil	29.1	27.7	29.1	27.7
SP	0.7649	0.7603	0.7019	0.6981
API	53.5	57.6	70.1	71.2
DISTILATION %Vole				
IBP	155	100		
10%	144	132		
20%	149	137		
30%	153	140		
40%	155	143		
50%	158	146		
60%	160	149		
70%	162	152		
80%	165	155		
90%	168	161		
EBI	197	186		
Recovery	99	99		
Loss%	0.5	0.5		
Residue	0.5	0.5		

Results and Discussion

Optimizing Energy Efficiency in Refining Units by Switching Heavy Naphtha for Light Naphtha Furnace Fuel

The refining industry has always struggled with the situation of finding a steady and affordable fuel supply to operate its activities. Dora refinery and the following setup of a new production unit, which has increased capacity, were to overcome the shortage of petroleum derivatives in the region. Considering that the refining process is highly dependent on the temperature and pressure, it is a major consideration to select and be able to use appropriate fuels in furnace operation.

Need for Alternative Fuel in Furnace Operation

The refining process usually starts with the heating of crude oil to about 300 degrees Celsius temperature which helps to separate different petroleum derivatives. These furnaces were first intended to utilize heavy naphtha. The scarcity and high prices of sourcing heavy naphtha produced by other refineries have, however, led to the development of alternative fuels. Storing heavy naphtha is also considered unnecessary since it will be mixed with light naphtha and undergo hydrotreatment. This dependence on the external sourcing of heavy naphtha not only comes at a high cost but also carries the risk of transportation.

Proposed Solution: Switching to Light Naphtha

The option of stored light naphtha as furnace fuel was suggested to alleviate the issues related to heavy naphtha. This replacement not only saves the cost of procurement and transportation risks but also lowers carbon emissions, offering an environmentally friendly alternative. The furnace of the refining unit has two primary stages of heating: indirect and direct heating. During the indirect heating process, crude oil is heated through heat exchangers using heat from products refined in the atmospheric distillation tower, which increases the temperature of crude oil to an average of 165-185 ^{o}C. This level can be used to make it economically viable since the temperature of the products leaving this level is cooled,

thus making sure that equipment and other workers are not subjected to risks. When direct heating is involved, crude oil is once more heated to 325-350 ^{o}C in the radiant part of the furnace. This is used to vaporize almost all the fractions that will be condensed at their dew point and produce several products that are transported to the waste tanks to undergo testing and later storage.

Furnace Design and Components

The furnace can be divided into three large zones that play a certain role in the heat transfer and energy efficiency processes: Stack Section, Convection Section, and Radiation Section. The Stack Section gives the exhaust gases a chimney through which they can leave the system. The Convection Section recuperates the heat of those hot gases and readjusts the energy into the system. Tubes that contain the Process Streams are mounted in the Radiation Section to which the majority of the heat source generated by the flame can be directed, along with insulation and reflective walls to allocate even the radiant heat. To accommodate the accidental circumstances concerning fire, safety is significantly extended in the construction of the furnace, which includes the fire suppression system. The overall interaction and setup of these parts is shown in Fig. 1. The furnace sections are strategically positioned and integrated as a way of achieving maximum thermal efficiency and safety in their operation.

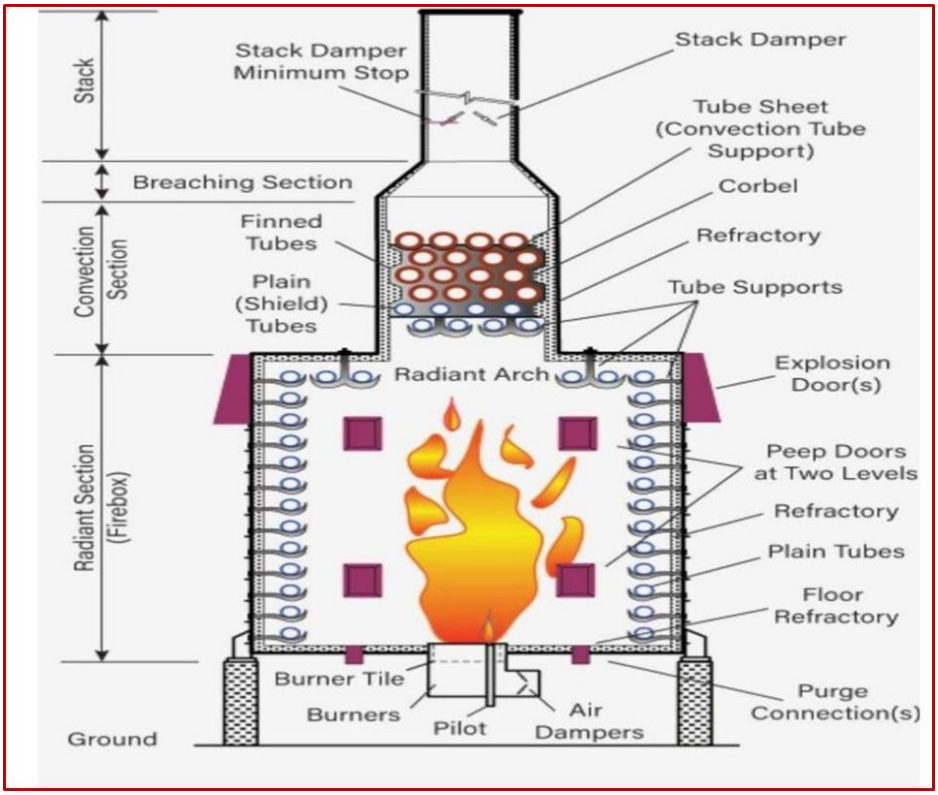


Fig. 1. Diagram of the furnace's three sections: stack, convection, and radiation.

Combustion Process in the Furnace

The law of combustion in a furnace in industry is always the reaction of a fuel with a generically-named oxidizing agent, typically oxygen. The fuels may be fuel oil, fuel gas, or both. To achieve good combustion and to ensure safety, one should always have more air than what is needed stoichiometrically. The excess air ratio is vital because it guarantees the

burning of all the fuel, the most efficient use of fuel, and the minimization of the chances of incomplete combustion, which may lead to unsafe working conditions and undesirable emissions. Having a desirable excess air ratio is, hence, a requisite of running the furnace, which is a balance between efficiency and running safety**.**

Switching to Light Naphtha Fuel

During planned unit shutdowns, light naphtha is often employed as an alternative fuel source. This switch necessitates modifications to the unit's infrastructure, including adjustments to the piping diagram and a carefully controlled ignition process to ensure a stable temperature increase in the furnace. The transition to light naphtha involves the following key steps:

1. Mechanical Adjustment to the Unit's Piping Diagram: A modification was made to the original unit design to facilitate the use of light naphtha as fuel. As illustrated in Figure 1, the adjustment involved connecting the light naphtha line, which exits pump P315, to the heavy naphtha line through the outlet pipe of controller FCV114. A normally closed valve was added at the connection point between the two lines. This adjustment allows for the controlled flow of light naphtha into the furnace system (Fig. 2).

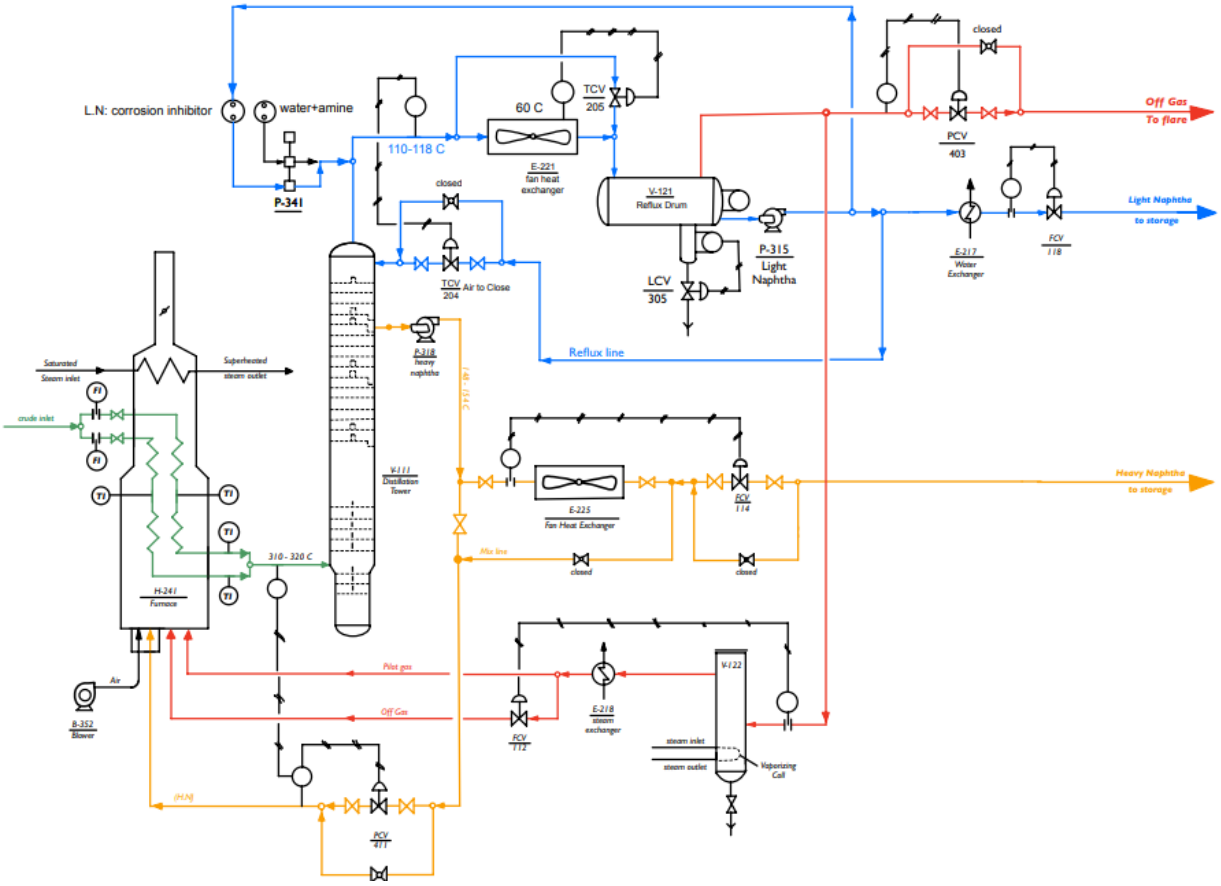


Fig. 2. A diagram showing the basic design of the unit

2. Pipe Connection Between Light and Heavy Naphtha Lines: Referring to Figure 3, the transition from heavy to light naphtha requires specific valve operations. The valve between the light and heavy naphtha lines is opened, while the outlet valve of FCV114 is closed, allowing its secondary passage to open. This sequence ensures that light naphtha passes through the pressure gauge positioned after controller PC411, which regulates fuel

supply to the furnace burners. The controlled introduction of light naphtha is essential for maintaining proper furnace operations during the fuel transition.

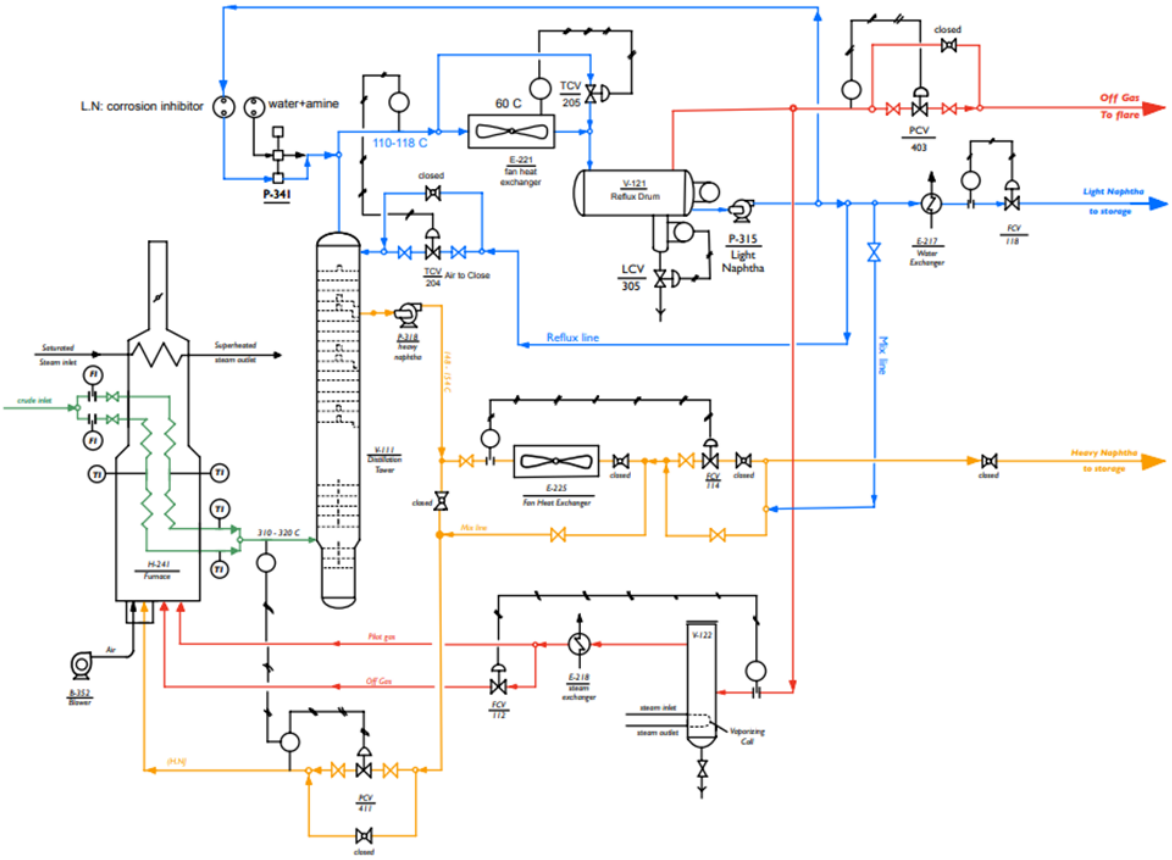


Fig. 3. A diagram showing the details of the tubular connection for the light and heavy naphtha lines after modification

3. Gradual Ignition of Burners Using Light Naphtha: Once the presence of light naphtha is confirmed through the pressure gauge (after PC411), the burners are ignited gradually. The recommended sequence for ignition starts from the center of the burners and moves toward the ends. This method ensures a steady and controlled increase in furnace temperature. By carefully managing the rate of temperature rise, thermal stresses are minimized, which preserves the crystalline structure of the furnace metals and reduces the risk of mechanical failures. This ignition process is critical for ensuring both the integrity of the furnace and the efficiency of the combustion process.

Economic and Cost Analysis of Utilizing Light Naphtha as Furnace Fuel in Najaf Refinery

Energy efficiency optimization is essential to the optimization of operations because it helps to reduce expenses and address environmental effects. The paper presents the economic feasibility of the process of substituting heavy naphtha with light naphtha as the furnace fuel in the Najaf Refinery, focusing on energy consumption, cost-comparison, and future long-term savings.

Energy Consumption and Cost Comparison

Energy usage of both light and heavy naphtha fuels was observed at long operating periods to determine the fuel efficiency under different temperatures. Table 2 shows the data on fuel consumption over the course of various intervals of furnace operation.

Table 2: patterns of fuel usage during various working hours

Operating Hours	Temperature (°C)	Light Naphtha Fuel (m^3)	Heavy Naphtha Fuel (m^3)	Gas Fuel Pressure
10:00 AM	25-50°C	0.2	----------	0
11:00 AM	50-100°C	0.6	----------	0.2
12:00 PM	100-150°C	1	----------	0.3
1:00 PM	150-200°C	0.9	----------	0.4
2:00 PM	200-250°C	0.3	0	0.5
3:00 PM	250-300°C	0	0.8	0.6

The light naphtha consumed was of the quantity of 3 cubic meters, equal to 3000 liters, with a unit price of 210 ID per liter, and its cost thus was 630,000 ID. On the other hand, heavy naphtha was consumed at a rate of 2 cubic meters, that is 2000 liters, with a higher price of 393 ID per liter, thereby its total cost amounts to 786,000 ID. This is balanced by the relatively lower price of light naphtha, so the overall cost was decreased.

Cost Savings and Economic Analysis

Switching to light naphtha presents marked savings, with the difference in cost of 156,000 ID for the period:

$$\text{Cost Difference} = \text{Total Cost of Heavy Naphtha} - \text{Total Cost of Light Naphtha}$$

$$= 786{,}000 \text{ Iraqi dinars} - 630{,}000 \text{ Iraqi dinars}$$

$$= 156{,}000 \text{ Iraqi dinars}$$

Although light naphtha was utilized in larger volumes, its unit price was lower and helped to bring down the fuel expenditure. The total savings from the substitution of fuels stood at around 20 percent of the overall fuel expenditure. Extrapolating this trend, a monthly saving of about 624,000 dinars can be realized, where the yearly savings come out to exceed 7.48 million dinars, hence a very economically viable solution for long-term operations.

Assessment of Environmental Impact and Emissions Reduction

One of the most important goals of environmental sustainability for the refining industry is the reduction of CO_2 emissions resulting from fuel combustion. This study will consider an appraisal of heavy naphtha replaced by light naphtha as a furnace fuel at the Najaf Refinery, taking into consideration an estimation of the reduction of CO_2 emissions.

Techniques for Emissions Reduction

The decrease in CO_2 emissions is based on the precombustion and post-combustion efforts. Precombustion control- like efficient fuel choice and consumption reduces the amount of carbon emitted directly during combustion. Substitution of heavy naphtha with light naphtha is a relevant precombustion measure. There is also the use of post-combustion methods, such as gas scrubbing, to reduce emissions in the air. This research focuses on the fuel-switching direction to boost energy efficiency and reduce CO_2 emissions.

Environmental Impact of Naphtha Fuel Combustion

The combustion of naphtha fuels releases carbon dioxide, water vapor, and heat, with the amount of CO_2 produced being directly related to the fuel's carbon content. The general combustion equation for hydrocarbons is:

$$C_nH_{2n+2} + MO_2 \rightarrow nCO_2 + (n/2 + 1)\ H_2O + Heat \qquad \textit{Equation 1}$$

Light naphtha, containing fewer carbon atoms (ranging from 5 to 8 carbon atoms), emits less CO_2 during combustion than heavy naphtha, which contains 9 to 13 carbon atoms. The following reactions highlight this difference in emissions:

Light Naphtha:

$$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O + Heat \qquad \textit{Equation 2}$$

Heavy Naphtha:

$$C_{12}H_{26} + 18.5O_2 \rightarrow 12CO_2 + 13H_2O + Heat \qquad \textit{Equation 3}$$

As illustrated, the combustion of light naphtha results in lower CO_2 emissions compared to heavy naphtha due to the reduced number of carbon atoms per molecule.

Quantifying Emissions Reduction

Table 3 compares the weight of oxygen needed to burn with the weight of CO_2 evolved by different hydrocarbons in light and heavy naphtha, thus quantifying the benefit to the environment of the change in light naphtha.

Table 3: Emissions Comparison between Light and Heavy Naphtha Combustion

Type of Naphtha	Chemical Formula	Oxygen Required	CO_2 Produced
Light Naphtha	C_5H_{12}	8	5
Light Naphtha	C_6H_{14}	9.5	6
Light Naphtha	C_7H_{16}	11	7
Light Naphtha	C_8H_{18}	12.5	8
Heavy Naphtha	C_9H_{20}	14	9
Heavy Naphtha	$C_{10}H_{22}$	15.5	10
Heavy Naphtha	$C_{11}H_{24}$	17	11
Heavy Naphtha	$C_{12}H_{26}$	18.5	12
Heavy Naphtha	$C_{13}H_{28}$	20	13

This result depicts that with an increase in the number of carbon atoms, the CO_2 produced increases. Thus, a substitution of heavy naphtha with light naphtha will result in efficient emission reductions

Environmental Benefits of Fuel Switching

The replacement of heavy by light naphtha as furnace fuel would provide significant environmental benefits. The light naphtha can consist of fewer carbon atoms, which implies lower CO_2 emission and a more environmentally friendly fuel composition. Reduction in the number of carbon atoms oxidized increases the efficiency of the refinery, hence limiting the carbon footprint. Moreover, light naphtha can reduce the production of other harmful pollutants like SO_x and NO_x that come with the emissions of CO_2, and thus improve the quality of ambient air. These advantages are in line with the worldwide industry trends, which are geared towards the reduction of greenhouse gas emissions and advancement of cleaner fuels.

Conclusions

The current paper supports the technical and operational viability of replacing heavy naphtha with light naphtha as furnace fuel in the Najaf Refinery. The replacement improves combustion efficiency and minimizes CO_2 emissions without negatively affecting operational stability and economic competitiveness. Due to the reduced carbon intensity and high energy efficiency, light naphtha is an effective alternative fuel to optimize furnaces. Its application enhances the effectiveness of refineries and the achievement of sustainability and reduction of emission goals.

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