CRUDE OIL REFINING

A Simplified Approach

Marcio Wagner da Silva

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Crude Oil Refining

This book provides an overview of crude oil refining processes and presents a deep analysis of the current context and challenges imposed on players in the downstream industry. *Crude Oil Refining: A Simplified Approach* covers traditional processes of the refining industry, the impact of current trends, and technological routes available to help these players survive in a highly competitive environment.

FEATURES

- Offers a simplified approach to crude oil refining processes
- Discusses economic information related to the downstream business, including refining margins and profitability
- Introduces newer trends in the industry, such as petrochemical integration, crude-to-chemicals refineries, and renewables coprocessing in crude oil refineries
- Presents the challenges related to these new trends and offers technological solutions to overcome them for profitable and sustainable operations
- Describes how the use of biofuels can minimize the environmental impact of transportation fuel in nations of high demand like Brazil

Offering a contemporary view of current challenges and opportunities in the downstream oil and gas business, this practical book is aimed at readers working in the fields of petroleum and chemical engineering.

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Contents

Preface

Despite new and cleaner energy sources, crude oil is still fundamental to sustaining the economic development of nations and the technological development of society. In recent decades, we have observed an increasing pressure on the crude oil industry to reduce the environmental impact of their processes and derivatives as a fundamental part of global efforts to reach a more efficient, cleaner, and sustainable society.

In this book, we deal with the processes applied to ensure higher added value to crude oil and the refining processes that are currently known as the downstream industry. The current scenario imposes great challenges to the players of the downstream industry, both due to the growing pressure to reduce the environmental footprint of their derivatives and the reduction in the demand for fossil transportation fuels.

Some trends and technologies, such as the electrification of automobile fleet and additive manufacturing, have the potential to destroy demand for crude oil derivatives, and this technological development requires high-quality derivatives, such as the base oils applied to produce lubricants, and these facts put refiners under pressure and squeeze the refining margins, leading players to look for new routes and processes to ensure high added value to processed crude oil. The objective of this book is to review classic crude oil refining processes and present an overview of the current scenario of the downstream industry and how the players can survive in this transitive period of the crude oil refining sector.

Acknowledgments

It's impossible to achieve any good result alone, and this book is no different. In this sense, I would like to start by giving my thanks to God! Without the support I received from my family, especially my wife, Ana Glaucia, and my daughter, Manuela, this book simply would not exist. I'm also grateful to the professionals with whom I had opportunities to exchange experiences and knowledge, especially Mr. Suleyman Ozmen, a real friend and an outstanding professional, as well as Mr. Romain Roux of Axens.

In my developing journey, I had the opportunity to learn at the State University of Maringa (UEM) and the State University of Campinas (UNICAMP), so I would like to express my thanks to all the good professors of the chemical engineering courses of both universities. The construction of this book relied on the contribution of some of the main technology developers to the crude oil refining industry, among them Chevron Lummus Global, Honeywell UOP, Axens, and Haldor Topsoe, as well as some of the most relevant trend/consultancy companies, such as IHS Markit, Wood Mackenzie, International Energy Agency (IEA), and the Catalyst Group companies. For all these companies, I offer my thanks.

Author

Marcio Wagner da Silva, PhD, is a process engineer and stockpiling manager in the crude oil refining industry based in São José dos Campos, Brazil. He earned a bachelor's in chemical engineering at the University of Maringa (UEM), Brazil, and a PhD in chemical engineering at the University of Campinas (UNICAMP), Brazil. Dr. da Silva has extensive experience in research, design, and construction in the oil and gas industry, including developing and coordinating projects for operational improvements and debottlenecking to bottom barrel units. Moreover, he earned an MBA in project management at the Federal University of Rio de Janeiro (UFRJ) in digital transformation at PUC/RS, and he is certified in business from the Getulio Vargas Foundation (FGV).

Recently Dr. da Silva has dedicated his efforts to learning and sharing knowledge about the crude oil refining industry and taking part as an industry adviser to the International Association of Certified Practicing Engineers (IACPE), a member of the advisory board of *The Catalyst Review Magazine* from the Catalyst Group, and a member of the advisory board of the Global Energy Transition Forum, which is strictly committed to minimizing the environmental impact of the energy industry in a realistic and sustainable manner.

1 Crude Oil

1.1 INTRODUCTION

Crude oil is a complex mixture of hydrocarbons, which occur naturally in the earth. Crude oil can be separated into fractions through distillation to achieve the most useful derivatives for society, like fuel and petrochemicals.

Choosing an adequate crude oil slate is among the most relevant decisions of refiners. Refining assets are designed considering a narrow range of characteristics of crude oil to be processed. However, over the useful life of the assets, crude oil slates to be processed can undergo great changes either due to a shortage of crude oil with certain characteristics or by supply difficulties linked to geopolitical issues.

The characterization and classification of different types of crude oil aim to establish its value primarily in relation to reference crudes like Brent and WTI (West Texas Intermediate), as well as define the technological and refining routes to adequate processing. Crude oil consists basically of a mixture of hydrocarbons and associated impurities. These impurities normally refer to sulfur, nitrogen, oxygen, and metals. The concentration of these impurities significantly raises the technological challenges of crude oil processing, leading to a reduction in the crude oil prices according to the concentration of the impurities. The determination of the crude slate to be processed in a refinery is based on a blending of crude oil, aiming to achieve an adequate composition of hydrocarbons and contaminants that allow the processing in a reliable and profitable manner. Figure 1.1 presents the main variables considered in the choice of crude oil slate to be processed in a refining asset.

Some scenarios, such as the discovery of abundant reserves of crude oil with characteristics different from those suitable for a given refining asset, can support the decision of capital investments aiming to adapt the refining assets to the processing of a certain type of crude oil. This fact is common when a refiner is an importer and oil reserves are discovered in the local market.

In relation to hydrocarbons, crude oil contains paraffinic, naphthenic, and aromatic molecules that confer the chemical and physical characteristics of crude oil.

Crude oil can be classified according to the physical and chemical characteristics of the hydrocarbons found in the geological reservoir, one of the most common classifications is the API grade, which is based on the specific gravity of crude oil as described in Equation 1.1.

$$API = \frac{141{,}5}{\rho} - 131{,}5 \tag{1.1}$$

Where ρ = specific gravity of crude oil

Table 1.1 presents an example of crude oil classification based on API. It's important to note that the API grade is a basic classification parameter of crude oil.

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FIGURE 1.1 Schematic Representation of the "Blending Space" of Crude Oil

TABLE 1.1
Crude Oil Classification Based on API Grade

Classification	API Grade
Light crude	API > 31,1
Medium crude	22, 3 > API < 31,1
Heavy crude	10,0 > API < 22,3
Extra-heavy crude	API < 10,0

Source: Adapted from Guidelines for Application of the Petroleum Resources Management System, 2011

A very relevant characteristic of oils for refining hardware is naphthenic acidity. Naphthenic acidity is determined based on the amount of KOH required to neutralize 1 gram of crude oil. Normally, a mixture of crude oil is sought in the refinery load so that it does not exceed 0.5 mg KOH/g. Above this reference, the bottom sections of the distillation units can undergo a severe corrosive process, leading to shorter periods of the operational campaign and higher operating costs in addition to problems associated with integrity and safety. Naphthenic acidity is directly linked to the concentration of oxygenated compounds in crude oil that tend to be concentrated in heavier fractions, giving instability and odor to the intermediate currents.

Another relevant characteristic of crude oil is the salt (NaCl) content. The presence of salt in the oil leads to serious corrosion problems, mainly in atmospheric distillation units. The salt content after desalting in atmospheric distillation units is controlled to be below 3 ppm.

Sulfur content is also one of the variables used in the characterization of crude oil in view of their impact on the emissions of harmful gases when using derivatives as fuels. In addition, sulfur compounds increase the polarity of raw oils, leading to stabilization of emulsions and greater difficulties in the desalting process. Normally, oils are classified as high in sulfur when they have levels above 0,5% by weight and low in sulfur below this reference. High-sulfur oils require greater hydrotreating capacity to meet the current environmental requirements for the commercialization of oil products. The presence of contaminants like sulfur, nitrogen, and oxygen is another relevant parameter to classify crude oil and has a great impact on defining the required processes needed to produce the required crude oil derivatives. Normally, the lighter crudes present higher yields of added-value streams like naphtha and diesel and less contaminant content, which lead these crudes to achieve higher prices in the international market. Nowadays, crude oil with low sulfur content tends to be more valuated in the market, especially due to the regulation IMO 2020 (the International Maritime Organization's rule on limiting sulfur emissions).

This regulation established that after 2020, the maximum sulfur content in the maritime transport fuel oil (bunker) is 0,5% (m.m) against the past 3,5% (m.m). The main objective is to reduce the SOx emissions from maritime fleets, significantly decreasing the environmental impact of this business.

Maritime fuel oil, known as bunker, is a relatively low-viscosity fuel oil applied in diesel cycle engines to a ship's movement. Before 2020, the bunker was produced through the blending of residual streams as vacuum residue and deasphalted oil with dilutants like heavy gas oil and light cycle oil (LCO). Due to the new regulation, a major part of the refiners will not be capable of producing low-sulfur bunker through a simple blend.

Due be produced from residual streams with high molecular weight, there is a tendency for contaminants accumulation (sulfur, nitrogen, and metals) in the bunker. This fact makes it difficult to meet the new regulation without additional treatment steps, which should lead to an increased production cost of this derivative and the necessity for modifications in the refining schemes of some refineries.

The first alternative to meet the IMO 2020 is the control of the sulfur content in crude oil that will be processed in the refinery. However, this solution limits the refinery's operational flexibility and restricts crude slate suppliers, which can be a threat in scenarios with geopolitical instabilities and crude oil price volatility.

According to related by Fitzgibbon et al. (2017), just only a small part of crude oil is capable of producing an atmospheric residue that meets the new requirement of the bunker sulfur content.

Due to the limitation in the supply of low-sulfur crudes, the use of residue upgrading technologies aiming to adequate the contaminants contained in the streams applied in the production of the bunker is an effective strategy.

Despite the challenges imposed by IMO 2020, some refiners and crude oil producers are positively exposed to the new regulation, like the Brazilian crudes from pre-salt reserves, Russian Ural reserves, and Britannic North Sea reserves.

The Brazilian pre-salt reserves offer low-sulfur crude oil, with sulfur content varying from 0,3% to 0,67% (in mass). These characteristics of the Brazilian crudes represent a great competitive advantage not only to the downstream sector, but it's important to consider the valuation of these crudes in the market considering the restrictions imposed by IMO 2020. Nowadays, the pre-salt reserves represent the main crude oil source for Brazilian refineries, and the Brazilian downstream sector can produce bunker in compliance with the IMO 2020 since 2019.

Nitrogen content is also a relevant characteristic of crude oil to be considered when choosing castings for processing at refineries. Nitrogen compounds tend to stabilize emulsions, leading to greater difficulties in desalting oil. In addition, they are responsible for imparting chemical instability to derivatives, leading to the formation of polymers and color changes, especially in aviation kerosene. Excess nitrogen compounds can also lead to the deactivation of the acid function of catalysts in deep conversion processes, such as FCC.

The metal content in crude oil is a relevant variable since, like other contaminants, it tends to be concentrated in heavier fractions of oil. These fractions tend to be processed in deep conversion units, such as hydrocracking and catalytic cracking, and they tend to plug the pores of the catalysts, leading to the rapid deactivation of these catalysts, significantly increasing operating costs, and requiring the installation of guard beds to protect the active catalysts.

As previously mentioned, crude oil considered light tends to be more valued in the market, especially in the current market scenario in which there is a tendency to increase the demand for petrochemical intermediaries to the detriment of transportation fuels.

The adequate characterization of crude oil allows for establishing the main challenges for its processing and the mixture of crude oil necessary to reach an adequate cast for each refining hardware, in terms of either profitability or the maximum contaminant levels allowed for reliable processing, and that ensures the integrity of operational assets.

1.2 PRIMARY TREATING PROCESSES OF CRUDE OIL

The reliability of the processing units is fundamental to allow refiners to achieve the desired reliability and keep the competitiveness and the consumer market supply. The operational continuity of a refinery relies on some factors and a strong management system. However, the quality of the raw material (crude oil) is one of the main factors in ensuring the reliability and integrity of the refining processes. Normally, crude oil that will be processed in the refineries must meet some quality requirements aiming to preserve the separation and conversion processing units, mainly the atmospheric distillation unit. The maximum water and sediment content in crude oil is controlled so that it will be lower than 1% in volume. Other relevant parameters are diluted salt content and the total acid number (TAN), which is defined as the quantity of KOH (potassium hydroxide) needed to neutralize 1 gram of crude oil.

To achieve these requirements, crude oil undergoes a series of treatments. This "primary treatment" aims to ensure the life cycle of the downstream and midstream assets. These processes are generally focused on separating water, gas, and oil phases

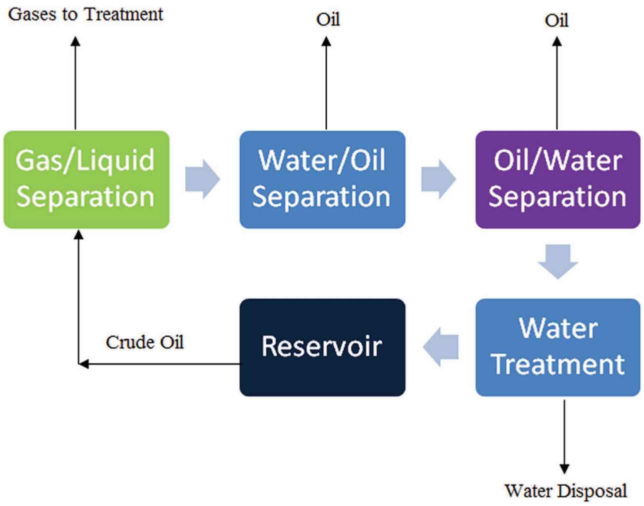

FIGURE 1.2 Steps of the Primary Treatment of Crude Oil

still in the upstream assets. Figure 1.2 shows the basic steps of the primary treatment of crude oil through a block diagram.

Crude oil is drawn from the reservoir, and the separation of gas and liquid phases is carried out through pressure reduction. In the next step, the liquid phase is pumped into a separator drum to promote the separation of oil and water phases by decantation. In this step, only the free water is separated from the oil. A part of the water is emulsified. Subsequently, the mixture undergoes a new treatment step by applying an electrical field and demulsifier addition beyond the heating that aims to reduce the viscosity and allow better phase separation.

The water-oil phase separation is carried out in decantation vessels, which can be two-phase, when it is realized just by the separation of gas and liquid (water + oil) phases, or three-phase, when it involves the separation of free water from oil additionally. Due to the high superficial area, the separation vessels have a normally horizontal configuration. However, in upstream units with great production flow rate oscillations and large sediment content, the vertical configuration is adopted.

In the oil-water-separation step, the emulsion is broken through the application of a high-intensity electrical field that promotes the water droplet polarization and, consequently, decantation. Unlike what occurs in the refineries during the crude desalting process, the electrical treaters used in the upstream assets are low-speed. In this case, the emulsion is fed in the bottom and distributed under a laminar regime to the internals of the separation vessel.

After the separation step, the water is directed to a treatment system. A simplified configuration of a typical water treatment unit is presented in Figure 1.3.

The brine coming from electrostatic treaters is pumped to degassing vessel to remove dissolved gases. After this step, the oily residue is directed to the tank where the phase separation occurs. The aqueous phase is sent to a new treating cycle

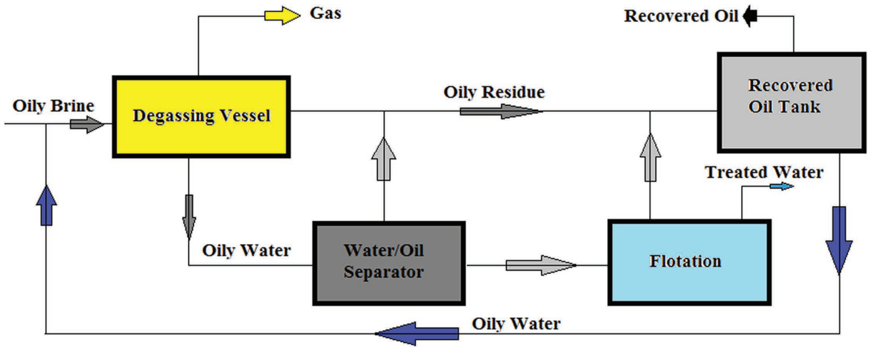

FIGURE 1.3 Oily Water Treatment Process

while the oily phase is pumped to storage. The oily water is directed to a water-oil-separation treatment step, which normally applies API separators. However, in modern sites, hydrocyclones are used due to their higher efficiency. After a flotation step, the treated water can be directed to be disposed of or to be reinjected into the reservoir to improve the recovery of crude oil.

Natural gas produced is directed to treatment steps aiming to reduce the humidity content and sour gases removing. The dehydrating process is carried out through the absorption process with TEG (triethylene glycol), while the sour gases ($H_2S + CO_2$) are removed through amine treatment.

The produced gas stream still undergoes treatment steps aiming to remove heavier compounds (C_3 to C_{5+}) that are considered condensable in natural gas. This process consists basically of the controlled refrigeration of the gas to condense the heavier fractions. The processes generally employed are the Joule-Thomson expansion, simple refrigeration, and turbo expansion. The obtained stream has a great added value and can be applied as a petrochemical feed stream due to its high paraffin content or, according to the consumer market, be directed to the refineries to improve the yield of LPG and gasoline.

As aforementioned, an adequate treatment of crude oil is fundamental to ensure the reliability and availability of the downstream industry. High salt and water content in the crudes leads to higher corrosion and deposition rates in the processing units, reducing the life cycle and increasing operational costs due to unplanned shutdowns. Other assets that experience strong degradation due to the failures in the primary treatment steps are the storage tanks and pipelines. In this sense, the integration between upstream and downstream systems is a key factor in ensuring the sustainability of the crude oil production chain.

When some of the controlled parameters are out of specification, it is necessary to blend different crudes to keep the feed stream to the crude oil distillation unit under controlled conditions. This fact raises the operational costs related to unnecessary operational handling that could be avoided.

Adequate asset management is an important step in the current transformation of the downstream industry. The management system needs to be based on two driving engines: the first is focused on keeping the current operations once they sustain the planned future, and the second is focused on innovative actions to ensure the pereniality of the business. This is an important consideration related to what is called digital transformation. This phenomenon is not only related to technology. Technological advancements make easy access to data possible, but we need a modern and strong management system able to ensure that the right questions will be done to transform these data into information, knowledge, and finally, wisdom.

1.3 CRUDE OIL DERIVATIVES

Crude oil processing produces a series of derivatives with distinct demands and added values. Figure 1.4 presents a simplified process flow diagram for a typical atmospheric crude oil distillation unit and the main derivatives produced in this unit.

The stream considered as fuel gas is normally composed of hydrocarbons in the range C_1 to C_2 and is applied as fuel in the fired heaters and boilers in the own refinery.

The main quality parameters controlled in the fuel gas are the humidity and hydrogen sulfide (H_2S) content. These requirements are normally controlled in dehydration units using propylene glycol and amine treating units, respectively. The concentration of H_2S is controlled to be below 1% in volume and humidity content.

LPG is normally composed of paraffinic and olefinic hydrocarbons in the range of C_3 to C_4 and is applied as domestic and transportation fuel in specific cases. The LPG can contain low quantities of light and heavy hydrocarbons (C_2 and C_5). However, the concentration of these compounds needs to be minimized, aiming not to lose the quality requirements. The concentration of light hydrocarbons is controlled through the Reid vapor pressure (RVP), which is determined by the LPG heating at 37,8°C. The light content is controlled for security reasons, aiming to keep the LPG volatility under safe values to allow storage and handling. The RVP of commercial LPG is controlled to be below 1430 kPa. Once LPG is normally burned into closed environments, the control of burning residue is one of the most important quality requirements of this derivative. The heavy content is controlled through weathering test that evaluates the difficulty in vaporization of LPG. Measuring in an indirect way, the content of C_{5+} in the mixture is normally defined by the boiling temperature of 95% in volume of the mixture under atmospheric pressure and is normally controlled to be below 2°C.

The naphtha streams are normally directed to the refinery gasoline pool according to the refining configuration and the demand of the market where the refiner is inserted. The streams that compose the gasoline pool also depend on the refining scheme. However, it's common for the composition of gasoline pool with straight-run naphtha, cracked naphtha from FCC units, reformed naphtha from catalytic reforming units, isomerized naphtha from isomerization units, and alkylated naphtha produced in catalytic alkylation units.

The gasoline is composed by the blending of these streams containing hydrocarbons with a boiling range of 30–215°C (C_4 to C_{10}). Among the main quality requirements of the gasoline are the antiknock capacity, volatility, corrosivity, pollutants emissions, and the tendency of combustion residue formation in the

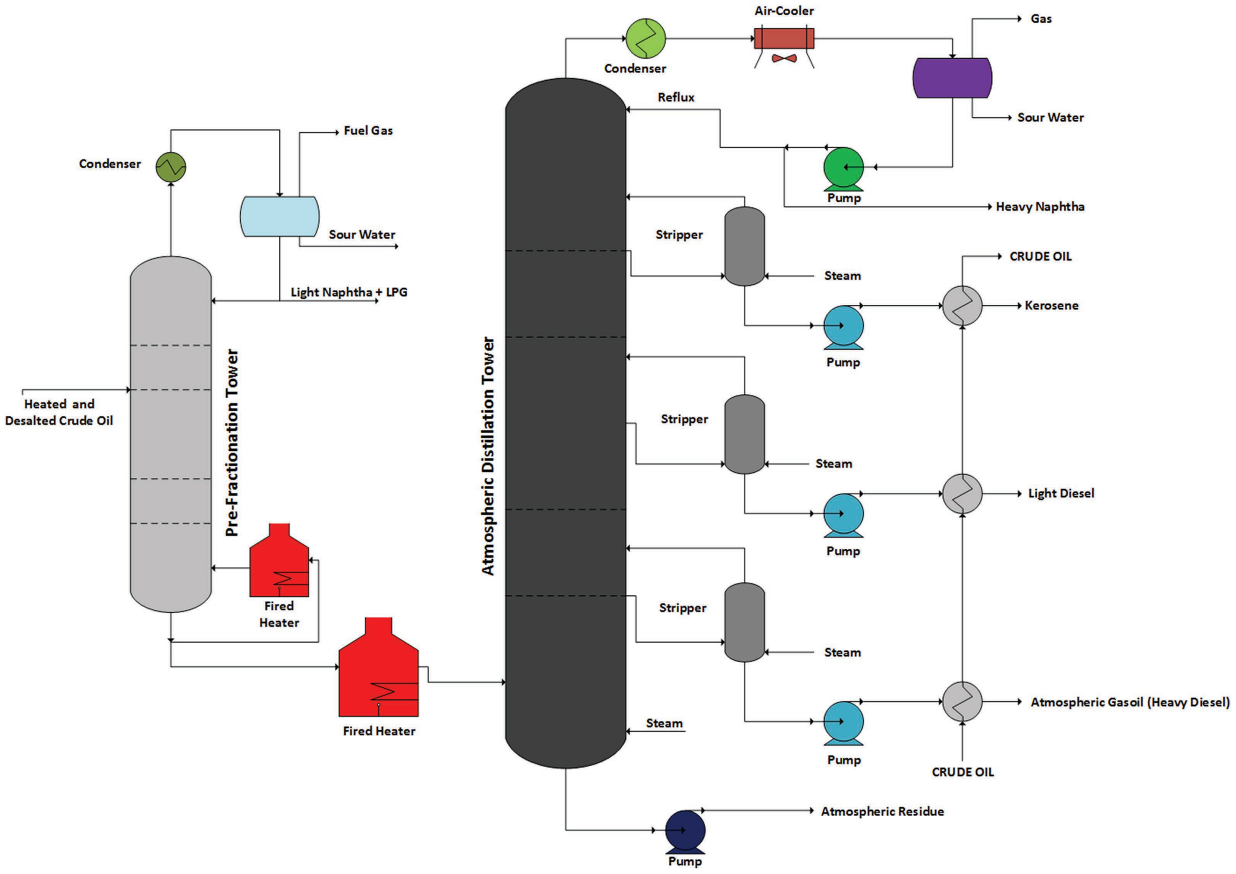

FIGURE 1.4 Typical Process Arrangement of an Atmospheric Crude Oil Distillation Unit

engines. The gasoline antiknock capacity is measured through the octane number that is determined by applying isooctane (2,2,4-trimethyl pentane) as standard with octane number 100 and the n-heptane with octane number 0. The octane number represents a volumetric percentage of isooctane in a mixture with n-heptane, which burns with the same antiknock quality of the analyzed gasoline (measured through sound intensity), the tests to determine the octane number can be the MON (motor octane number) test and the RON (research octane number) test. Common automotive gasoline has an octane number close to 85. The naphtha streams that add higher antiknock capacity to the gasoline are the cracked naphtha from FCC units due to the high olefin content, the reformed naphtha due to the high aromatic concentration, and the naphtha from catalytic alkylation due to the ramified characteristics of the produced kinds of paraffin. However, the aromatic and olefin contents are normally controlled in the final gasoline due to the toxicity and high volatility of these compounds.

The volatility of gasoline is related to the light content in the mixture being directly responsible for the cold starting facility of the internal combustion engines. Gasoline Reid vapor pressure (PVR) indirectly measures the amount of light present in the blend, and for LPG, the gasoline PVR is determined at 37,8°C (100°F) at 1 atm and is usually controlled to be below 55 kPa.

The corrosivity and emissions of the gasoline are controlled through the sulfur content in the final product. Currently, the sulfur content in the gasoline is controlled to be below 50 ppm. For this reason, it's practically impossible to meet this specification without hydrotreating units. Selective hydrotreating units are applied mainly to treat cracked naphtha aiming to reduce the sulfur content with minimum loss of antiknock capacity (due to olefin saturation). The resistance of deposit formation is directly related to the olefin content in the mixture. These compounds are chemically unstable and undergo polymerization, forming polymers that produce deposits and inefficient combustion. The use of antioxidant additives and detergents in the final gasoline can minimize these effects.

A special case of commercialized gasoline is the aviation gasoline that is applied to airplanes equipped with Otto cycle engines. In this case, the hydrocarbons that compose the gasoline have a stricter boiling range (30–170°C) containing ramified paraffin produced by catalytic alkylation processing units.

According to the market to be supplied and the interaction level of petrochemical and refining operations, the light straight-run naphtha can be commercialized as petrochemical naphtha. In this case, it's necessary to guarantee a paraffin content higher than 65%. This alternative tends to be even more applied face with the tendency for a reduction of transportation fuel demand. Furthermore, in markets with high demand by middle distillates, the heavy straight-run naphtha can be directed to compose the diesel or jet fuel pool.

In its turn, jet fuel is a mixture of hydrocarbons between C_5 and C_{15} with a boiling range of 150–300°C; it is applied as fuel to jet turbines, normally applied in aviation. Due to the severity of use conditions, jet fuel has quality requirements quite restricted. The combustion needs to be the cleaner possible to avoid depositions. For this reason, the polyaromatic content is controlled. This is achieved through the smoke point test.

The characteristics of flow under low temperatures are fundamental to jet fuel due to the operational conditions that can achieve temperatures of −50°C. The maximum freezing point for commercial jet fuel is −47°C. For this reason, it's fundamental to ensure an adequate cut point in the distillation step to avoid the drag of heavy paraffin to the intermediate kerosene. The thermal stability is measured through the JFTOT (jet fuel thermal oxidation test), which simulates the operational conditions that the fuel is submitted to.

The corrosivity and chemical stability in relation to the materials applied to the construction of turbines are controlled through the content of total sulfur, mercaptan sulfur, and H_2S. Normally, jet fuel is submitted to a caustic treating step to control these compounds. In modern refining units, this step is carried out in hydrotreating units. The flash point (minimum 40°C) and the electric conductivity are other requirements directly related to the security in the derivative handling.

Diesel is a crude oil derivative that had the most increased demand in the last decades. This derivative is mainly used as a transportation fuel by vehicles equipped with diesel cycle engines and is composed of hydrocarbons between C_{10} and C_{25} with a boiling range of 150–380°C. The diesel ignition quality is measured through the cetane number that corresponds to a volumetric percentage of cetane (n-hexadecane) in a mixture with heptamethylnonane, which burns with the same ignition quality as the analyzed diesel. The linear paraffinic hydrocarbons are the compounds that most contribute to the diesel ignition quality, raising the cetane number while the presence of aromatics reduces this parameter and harms the ignition quality. Currently, the minimum cetane number of commercial diesel is 48. In some countries, like Brazil, the addition of biodiesel in the final product is mandatory, with a minimum concentration of 10% in volume.

The diesel volatility is controlled, aiming to ensure the cold start performance and safety during the handling. The minimum flash point of 38°C and the temperatures of distillation curve correspondent to 50%, 85%, and 95% recovered in volume are controlled in determined limits to ensure the total vaporization in the working conditions. These parameters limit the quantity of naphtha added to the diesel pool.

Another important parameter controlled in the diesel is the plugging point that aims to control the content of linear paraffin that tends to crystallize under low temperatures harm the fuel supply to the engine. The plugging point is determined according to the weather conditions in the region of application. In Brazil, the plugging point is controlled in the range of 0–10°C.

The diesel emissions control is carried out by managing the fuel density aiming to control the content of heavy compounds, especially polyaromatics. Currently, the density of commercial diesel is controlled in the range of 830–865 kg/m^3 to ultra-low-sulfur diesel (ULSD). This parameter is controlled to be below 850 kg/m^3. In the last decades, there have been great efforts to reduce the environmental damage produced by diesel burn. Nowadays, environmental regulations require the commercialization of low-sulfur diesel with a maximum sulfur content of 10 ppm. However, in some markets, mainly in developing countries, there is still commercialized diesel with higher sulfur content (500 ppm), but this will change soon. This requirement led to the necessity of refiners to expand their hydrotreating capacity.

The viscosity is also a controlled parameter in the diesel, aiming to ensure an adequate nebulization in the combustion chamber. High viscosities can be bad due to the poor dispersion of the fuel, while low viscosities lead to excessive dispersion. Normally, the diesel viscosity is controlled in a range of 2–5 mm^2/s. The diesel lubricity is measured to control the wear due to the friction of the pieces in contact with diesel and is determined by specific tests. The lubricity and the electric conductivity are directly related to the concentration of polar compounds that are reduced after the hydrotreating step. For ULSD, additives are normally used to correct these parameters.

The control of water content and sulfur, nitrogen, and aromatic compounds aims to avoid the proliferation of microorganisms that lead to the filters plugging and add corrosivity to the derivative, as well as raise the stability of oxidation and deposit formation.

Adequate management of crude oil derivative quality requirements is fundamental to achieving the desired goals of performance, safety, and environmental impact. Ensuring the efficiency and reliability of the process responsible for controlling these parameters is a key factor in achieving competitiveness and sustainability in the refining industry.

The fuel oil formulation is carried out by adding diluents to vacuum residue, aiming to achieve a specified viscosity according to the application. Commonly, diluents applied are the gas oil streams from vacuum distillation or streams from deep conversion units like FCC (light cycle oil) or delayed coking (light and heavy gas oils). In some cases, diesel is applied as diluent. The main quality parameters controlled in the fuel oil production are sulfur content, viscosity, the content of sediments and water, vanadium concentration, flash point, and pour point.

The fuel oil is considered a low-sulfur fuel when the maximum concentration of this contaminant is 1% is mass and high-sulfur fuel when the maximum sulfur concentration is 2,5%. The sulfur content control aims to impose a limit on the emissions of harmful gases during the derivative burning. The viscosity control in the fuel oil aims to minimize the transfer costs and ensure adequate flow and vaporization in the burners. The kinematic viscosity of industrial fuel oils (measured at 60°C) is controlled in the range of 600–950 mm^2/s.

The limit of water and sediment content aims to minimize the fouling, deposition, and corrosion in the process equipment and damage to the burners. Furthermore, the water presence reduces the calorific value once part of the released energy is applied to vaporize the water and can provoke flame instability. The maximum vanadium content control aims to minimize the effects of the chemical attack of this metal on the refractory of boilers and fired heaters, as well as metallurgic damages. The maximum vanadium content in the fuel oil is 200 ppm. In its turn, the flash point is applied to control the fugitive emissions and add security during the derivative handling, while the pour point aims to ensure the flow under low temperatures. The pour point specification relies on the weather conditions in the application region.

In some cases, it's necessary to mix different fuel oils to meet the quality requirements. In these cases, it's important to consider the compatibility between the fuel oils. Oils from highly paraffinic crudes show chemical incompatibility with oils produced from crude oil with high asphaltene content, once the presence of paraffin precipitates the asphaltenes due to the resin solubilization that stabilizes the asphaltenes in the solution.

Asphalt is considered a residual fraction of crude oil, normally composed of molecules predominantly aromatic. Asphalt is produced from the vacuum residue that is obtained in the bottom of the vacuum tower, as stated earlier, or from the dilution of the asphaltic residue obtained from the solvent deasphalting process.

The main application of asphalt is the composition of road pavements. Among the asphalt quality requirements are consistency, hardness, ductility, thermoplasticity, viscoelasticity, thermal susceptibility, and durability.

The determination of consistency and hardness of the asphalt aims to define the handling capacity of the derivative. This variable is evaluated by the penetration test, which is performed using a standard needle under specific conditions of loading, temperature, and time. The ductility measures the ability of the asphalt to elongate before rupture. This requirement is directly linked to the strength of the material when applied to the pavement composition.

The thermoplasticity and the viscoelasticity are controlled, aiming at the possibility of hot application of the asphalt and the restoration of the properties of the material after cooling. Thermal susceptibility gives the asphalt the ability to withstand temperature variations without the loss of properties such as consistency and ductility. In turn, the durability test is performed under an aggressive atmosphere of exposure to air and heat, and the other properties are subsequently re-evaluated. The asphalt flash point is controlled to be below 235°C to allow safe handling of the derivative.

The marine fuel oils, called bunkers, are produced from the bottom residue of vacuum distillation. These derivatives are applied as fuels to large ships that operate with diesel cycle engines. Thus, despite also being produced from vacuum residue, the bunker oils have quality requirements different and more severe than the industrial fuel oils.

Due to the bunker's use in diesel engines, it is necessary to control the ignition quality of the bunker. This requirement is evaluated indirectly through the CCAI (calculated carbon aromaticity index), which is evaluated from the density and viscosity parameters that are controlled.

Viscosity is an extremely important variable for the bunker since it is directly related to the ease of nebulization of the derivative in the combustion chamber. High-viscosity oils require a higher heating rate before firing. The bunker viscosity is generally controlled between 2 and 11 mm^2/s (measured at 40°C). Another important feature is the pour point of the bunker. This variable depends on the climatic conditions in the region of application since it is related to the capacity to flow at reduced temperatures, and the bunker pour point is normally controlled between −6°C and 6°C.

The density of the commercial bunker is controlled between 877 and 897 kg/m^3, while the minimum flash point is 60°C to limit fugitive emissions and give safety to the handling of the product. The maximum water and sediment content for the commercialization of the bunker is 0,4% by volume to avoid corrosion and waste deposition in equipment and storage tanks.

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