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Review article

Advancement in heavy oil upgrading and sustainable exploration emerging technologies

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ABSTRACT

Upgrading heavy oil is a subject of high importance for fossil fuel industry due to the rapid depletion of light oil reservoirs and the consequent increased demand for upgrading heavy oil. In this review, the advancement made in heavy oil upgrading and the proposed sustainable emerging technologies dedicated to heavy oil processing have been discussed in a comprehensive and informative manner with consideration to the encountered associated with properties of heavy oil including its significant content of undesirable large molecular weight hydrocarbons, its high viscosity, and its elevated impurity level. The shortcomings of conventional crude oil upgrading technologies are outlined, in relation to the upgrading of heavy oil. The various technologies used for the extraction of heavy oil from reservoirs, as well as refinery technologies for improving the quality and marketability of heavy oil products are summarized encompassing modified conventional methods and emerging technologies. Thermal and catalytic processes were compared and evaluated based on the literature for heavy oil processing. Furthermore, emerging technologies for heavy oil processing were listed and discussed comprehensively. The proper selection of the refining technology for heavy oil processing is crucial for the quality of the final products and it is evident from the literature that the selection criteria vary from one heavy oil reservoir to the other depending on the properties of the crude oil.

1. Introduction and challenges

The fast depletion of conventional oil resources due to the increasing energy demand as shown in (Fig. 1**a**) calls for the recovery of other unconventional energy sources such as heavy oil and oil sands. The proportion of light crude in oil reservoirs has decreased, while heavy oil still accounts for the largest share of oil reserves. Therefore, heavy oil reservoirs represent future and global energy reserves to supplement the global energy demand as part of the energy mix solution (Fig. 1b) which are becoming more and more critical particularly with the declining light oil resources. Therefore, the advancement in upgrading heavy oil becomes of immense important to the fossil fuel industry. However, the production and utilization of heavy oil has many technical and environmental challenges that need to be addressed which are discussed in this review in a comprehensive and informative manner including extensive overviewing of the emerging technologies related to heavy oil processing (Marafi et al., 2019; Varfolomeev,et al., 2023). These distinctive challenges posed by heavy oil are many that include but not limited to the substantial content of undesirable high molecular weight hydrocarbons, large viscosity and density, high level of impurities that are discussed as well. Heavy oil, like conventional crude oil, is initially located in a certain depth. Nevertheless, when it floats to the surface, its

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content of light hydrocarbons is lost due to the high volatility of these compounds along with the occurrence of bio and physical degradation. Additionally, almost all the difficulties faced during the recovery and processing of heavy oil originate from its composition, which includes high contents of asphaltene, resin, sulfur, and heavy metals, which are molecules of low **hydrogen to carbon** (H/C) ratio and high insolubility that increase the viscosity of the oil and hinder its flow. These molecules still pose a challenge for the fossil fuel industry, but the abundance of heavy oil reservoirs and their availability as an energy source for future use, has compelled an important academic and industrial effort concerning the recovery and processing of heavy oil (Hein, 2006, Speight, 2006, Eskin et al., 2016, Rana et al., 2017).

Many technologies have been developed and proposed for upgrading heavy crude and residue oil over the years. Such technologies comprise processes founded on carbon rejection, the addition of hydrogen, and a combination of the two, with the latter exhibiting a greater level of commercial viability in the past (Speight, 2006). Yet, various limitations have been identified for such technologies, particularly for the heavier oil, which necessitates the adoption of other cost-effective technologies (Hein, 2006). What makes a crude oil heavy is its high content of complex hydrocarbons such as asphaltene and resin that have core aromatic molecules with side chain hydrocarbons. This composition is the reason behind the low American Petroleum Institute (API) gravity of heavy oil which is between $22 and 10$, according to the American Petroleum Institute (API) (Hein, 2006). On the other hand, the API gravity of light oil is 34 or greater, while an API gravity between 31 and 33 indicates oil of medium nature. Thus, the value and marketability of crude oil increases with the increase of its API gravity (Hein, 2006). Besides, the heavy oils' complex hydrocarbons have a higher molecular weight and a large concentration of heterogeneous elements, including oxygen (*O*), nitrogen (*N*), sulfur (*S*), and metals (Speight, 2006).

Essentially, heavy oil is a form of crude oil that is highly viscous and is hard to flow easily (Rana et al., 2017). The heaviness of the oil is attributed to the low hydrogen to carbon ratio in the molecules and to other minerals that contribute to increasing the density of the oil (Rana et al., 2017). The most significant proportion of heavy oil deposits is degraded leftovers of conventional oils. The degradation occurs when the oil migrates towards the earth's surface and encounters water with bacteria and oxygen (Speight, 2006). This occurrence leads to the formation of a tar-like material that invades the oil accumulation. Processes such as water-flooding are used to remove water-soluble light hydrocarbons, which consequently leads to the accumulation of the unextracted heavy oil in the reservoir (Hein, 2006). Therefore, due to the high density and viscosity of heavy oil, unique extraction methods from reservoir are necessary to recover it efficiently (Hein, 2006; Zhou et al., 2023). Thermal recovery, cold production, and surface mining are some of the methods used for recovering from the reservoir and upgrading heavy oil. However, the use of these methods is accompanied with the

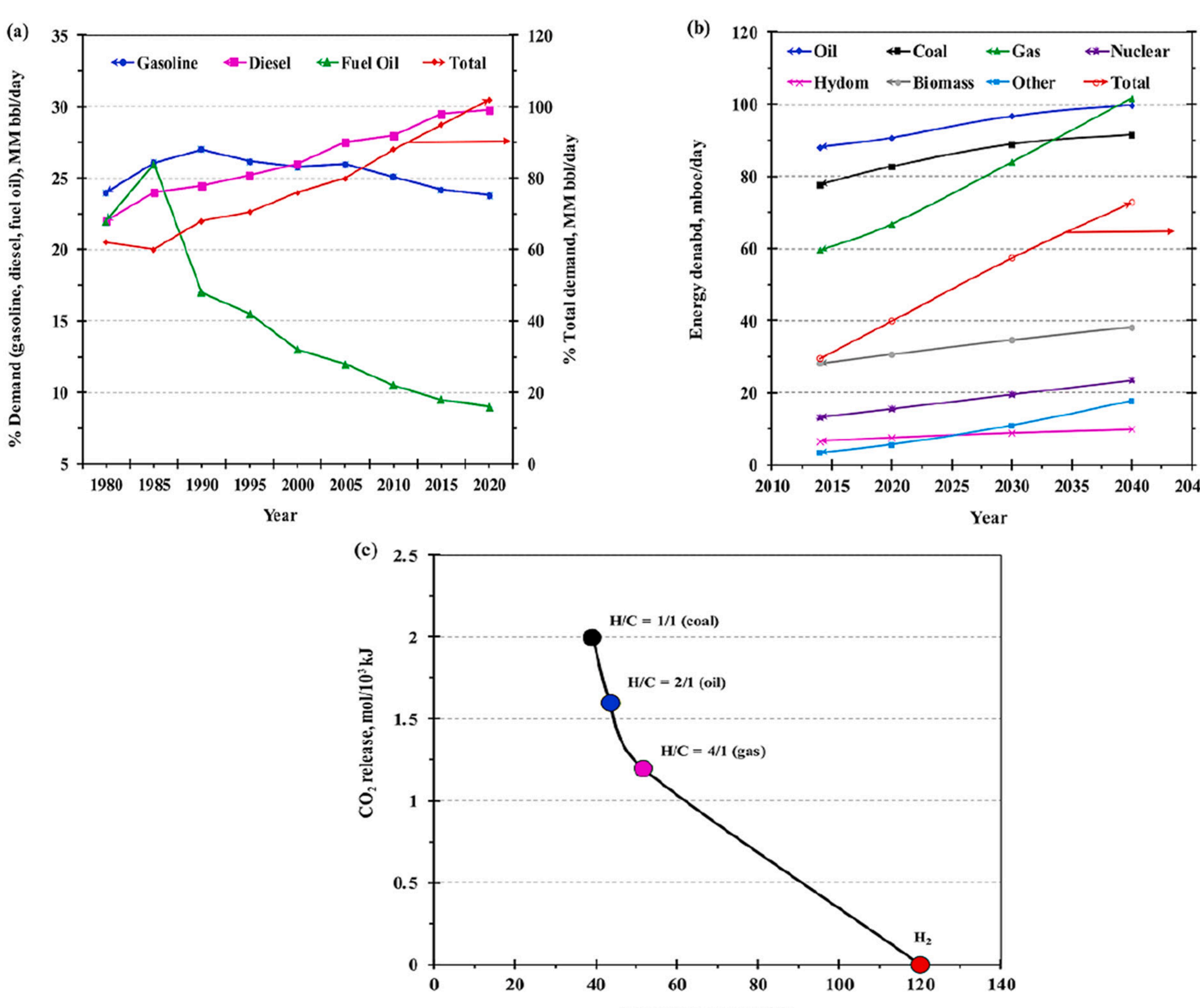

Fig. 1. Oil and energy demand along with energy content with CO_2 release. (a) Worldwide petroleum fraction demand, (b) energy resources and future demand, and (c) their fuel energy content and CO_2 evolution (Rana et al., 2017).

emission of greenhouse gases and other complex environmental impacts. Additionally, heavy oils require additional processing to enable effective refining and transportation. Therefore, significant amounts of energy are consumed for the production and extraction from reservoir of heavy oil. The demand for fossil fuel is increasing with time, driven by the rising energy demand as shown in Fig. 1**a, and 1b**. However, the composition of fossil fuel significantly affects the energy content as well as CO_2 release during their combustion as illustrated in Fig. 1**c**. The increase of the H/C ratio has a pronounced effect on both the increase of the energy content of the fuel as well as the reduction of the CO_2 emission due to lower carbon content in the composition of the fuel. The increase of the hydrogen content in fossil fuel and thus, the increase of the H/C ratio can be achieved by using refining processes such as hydro processing (hydrotreating and hydrocracking).

Another challenge is that heavy oil deposits are usually found at certain depths ($< 200m$) where the reservoirs are hydraulically connected to groundwater aquifers, or in contact with the atmosphere at the surface. For instance, in the United States, heavy oil is mainly produced in situ in shallow reservoirs (Hein, 2006). Most of these heavy oil deposits occur in shallow (3000*ftorless*) sandstone formations, which are poorly consolidated and relatively thick, with high permeability (Darcy grade), high porosity and oil saturation (Temizel et al., 2018). However, identifying the best recovery methods to adopt is made difficult by the in situ viscosity of the oil being highly influenced by the variation of the temperature and pressure conditions in the heavy oil formations (Temizel et al., 2018; Suwaid et al., 2023). Table 1 shows the most important recovery methods for heavy oil reservoirs.

Asphaltene, which is soluble in aromatic solvents but insoluble in an excess amount of paraffinic solvents, is present in most crude oil reservoirs. Due to its high molecular weight, its insolubility in crude oil and its tendency to aggregate in solutions and precipitate, asphaltene is considered as the reason behind many problems related to the extraction and the production of crude heavy oil. One of the main problems that are associated with the presence of high asphaltene content in the crude oil is *formation damage*, which is defined as the reduction or impairment of the permeability of a reservoir rock. This phenomenon is an undesirable occurrence with several negative impacts, the most severe being the reduction of the natural productivity of the reservoirs. Formation damage is usually reported at the wellhead but can occur at various stages of oil recovery from subsurface reservoirs. The decrease of the effective hydrocarbon mobility is another big problem resulting from the precipitation of asphaltene and other organics in the rock texture. These precipitated materials block pore throats and reduce cross-sections, increase the oil-wettability of the formation by absorption into rock surfaces and augment the stability of water-in-oil materials (Eskin et al., 2016).

To overcome these challenges, studies with the implementation of experimental, analytical, and modelling methodologies is critical in developing techniques for preventing and managing formation damage and other undesirable problems related to the presence of asphaltene in the oil reservoirs (Eskin et al., 2016). The impact of the presence of asphaltene is not only confined to the recovery and production of heavy oil, but their effects extend to the upstream operations as well, where a range of cracking technologies based on thermal cracking, catalytic cracking, hydro conversion, and a general refinery evolution have been introduced in an effort to minimize the negative effect of asphaltene (Guo et al., 2016). These procedures differ in terms of cracking method, cracked product patterns, and product qualities are used in refineries based on their characteristics (Guo et al., 2016).

Table 1
Most Important Recovery Methods for Heavy Oil Reservoirs (Temizel et al., 2018).

Thermal Recovery Methods	Nonthermal Recovery Methods
• Cyclic Steam Injection	• Water flooding
Steam Injection	Cold production
In Situ Combustion	Surface mining
Steam Assisted Gravity Drainage	Polymer Injection
Electromagnetic Heating	Vapor Assisted Petroleum Extraction
Steam Over Solvent Injection	Alkali Surfactant Injection
Nano-catalyst	CO_2 Injection
	Cold Heavy Oil Production with Sand
	Foamy Heavy Oil Production

Furthermore, using varying feedstocks in an existing refinery is not a straightforward task. As a result, when recovering heavy oil, extra-heavy oil, and tar sand bitumen, one of the most critical decisions is to consider whether to implement practical elements of upgrading during recovery, partial upgrading at the surface, or complete upgrading in a conversion refinery. Heavy oil upgrading is a concern for refiners and researchers, catalyst suppliers, and process developers, who have invested considerable time and resources into developing modern technologies and procedures to attain a high conversion rate and upgrade heavy oil and its residue into valuable products (Ancheyta et al., 2005; Rana et al., 2020; Parkhomchuk et al., 2023; Schacht-Hernández et al., 2023).

Various thermal processes (such as Vis breaking, delayed coking, gasification, etc.) (Carrillo and Corredor, 2013, Castaneda et al., 2014) as well as hydro processing methods such as the Hyvahl process (Axens), OCR (CLG), ARDS (Unicol), H-Oil (Axens/IFP), LC-Fining (CLG), and HYCON have been utilized in refineries depending on the types of the required products (Castaneda et al., 2014). The evaluation begins with a thorough grasp of the nature of the feedstock and an assessment of the conversion chemistry and process.

Upon the emergence of such technologies, the present review will explore the most cost-effective processing technologies adopted in heavy oil upgrading. Therefore, the objective of this manuscript is to provide an overview on heavy oil extraction and upgrading, the sustainable emerging technologies used, the available heavy oil options and their prices, the energy demand and marketing, and the related processing challenges. The use of heavy oil in the refinery as a feedstock and the investigation of the alternative energy resources used to lower the energy cost related to the extraction and processing of heavy oil are also covered in this review. The emerging technologies that can enhance the cost-efficiency and marketability of heavy oil are discussed comprehensively.

2. Heavy oil price and the related issues

The price of fossil fuel reflects market volatility. It is also a benchmark for global economic activity. Heavy oils and lighter oils are traded in the stock exchange markets. Crude oil options are traded in derivative product markets all over the world. There is a differential in the prices of crude oil arising from the difference in the gravity and the weight of oils (Guo et al., 2016). The price differential of crude oil attracts oil producers, who are inclined to maximize their profit, to concentrate their drilling and exploration efforts in areas most likely to produce lighter oils (Guo et al., 2016). The costly recovery and development processes of heavy oil, especially thermal development, are also a major reason why heavy oil reservoirs are avoided in favor of light oil reservoirs, which only require conventional and cost-efficient development techniques (Sun et al., 2023; Yuan et al., 2023; Hosny et al., 2023; Simonsen et al., 2024; Low et al., 2023; Li et al., 2023). Therefore, special attention should be paid to lowering the cost of developing heavy oil to ensure economic feasibility. Such attention is based on the fact that the current cost basis of heavy oil projects shows that energy costs account for approximately 35% of unit technology costs and more than 65% of operating expenses per barrel (Al-Yatama et al., 2018). There is also a committed effort by the organization of petroleum exporting countries (OPEC) aimed at finding cost-efficient alternative energy sources for steam power generation needed for the development of heavy oil.

Fig. 2**a, and b** present the average annual OPEC crude oil price and the variation of the price of the first purchase of several types of American crude oil over the last 42 years. Regardless of the crude oil's

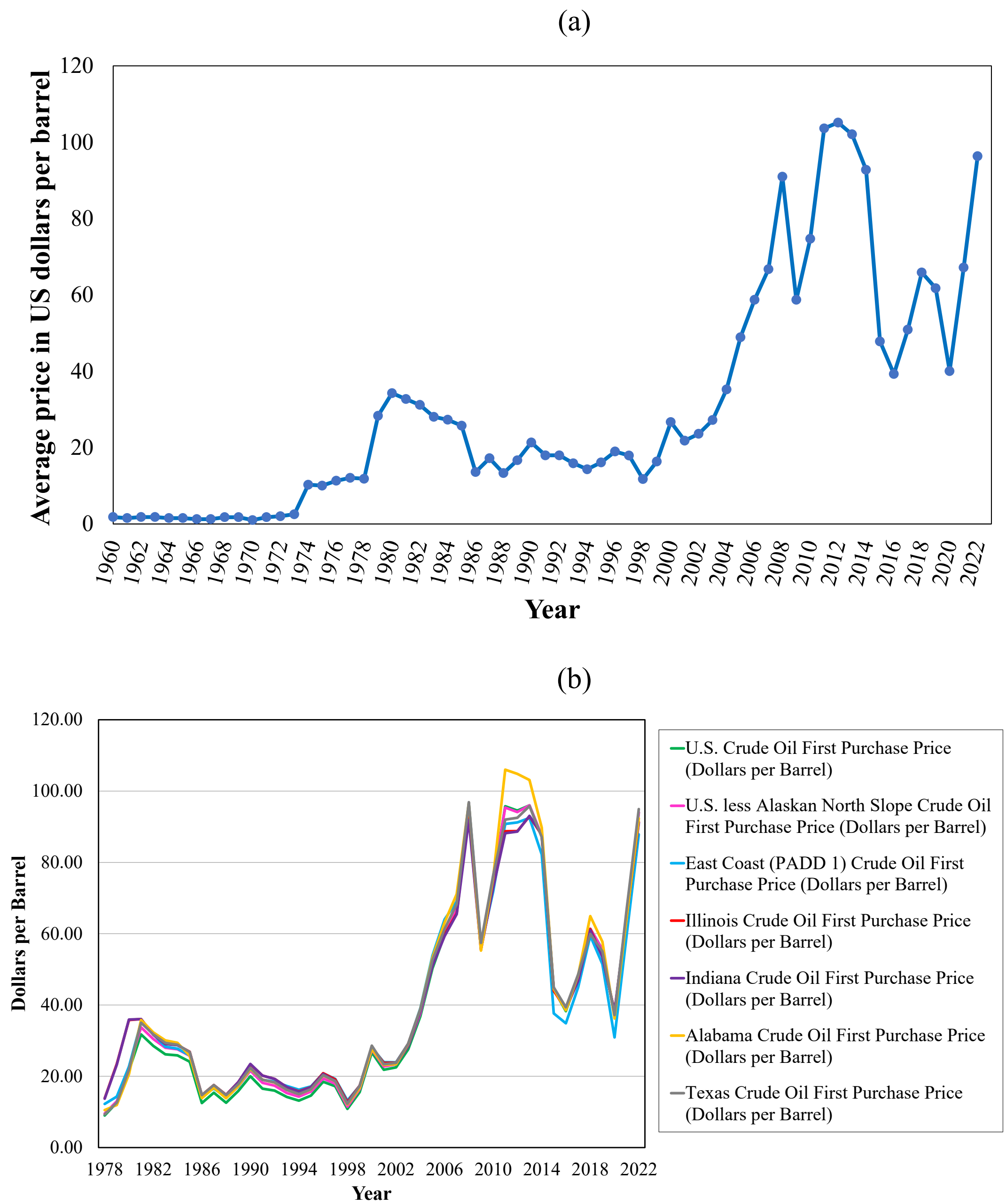

Fig. 2. Prices of crude oil (a) Average annual OPEC crude oil price from, 1960 to 2022 (US EIA, 2021); (b) US Domestic Crude Oil First Purchase Prices by Area in the USA from 1978 to 2022 (Argyle and Bartholomew, 2015, Average annual OPEC crude oil price from, 1960 to 2023).

origin, their prices followed the same trend over the years with $20-22\,USD$ being the maximum price difference per barrel between the most expensive and least expensive crude oil.

3. Energy demand and heavy oil market

Global energy demand has been rising due to population growth, increased level of living, the diversification of economic activities and urban expansion, all of which require increasing energy consumption. This has led to an increase in the production of crude oil globally, as shown in Fig. 3, with some fluctuation due to geopolitical issues. The production of heavy oil is increasing rapidly, especially in Venezuela, where significant efforts are invested in marketing the country's huge heavy oil reservoirs (Monaldi, 2015). However, it is hard to obtain data on the price variation of heavy oil alone, with heavy oil being more costly to produce and harder to market (Jefferson, 2020).

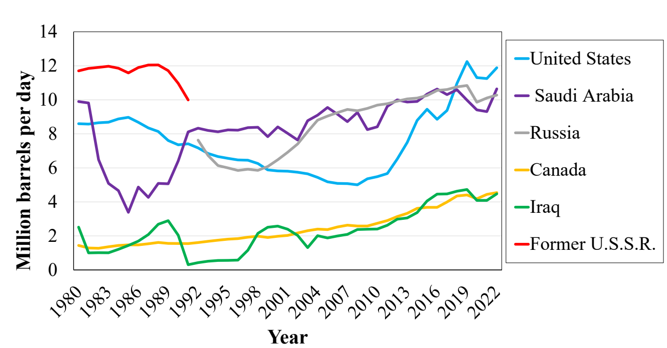

Fig. 3. Annual production of the top five crude oil producing countries 1980–2022 (U.S. Energy Information Administration April 1, 2021).

The viscosity and high density of heavy oil have made the exploitation of the important heavy oil resources more challenging compared to lighter oils (U.S. Energy Information Administration April 1, 2021). The nature and high molecular weight of hydrocarbons, to be specific, partly determine the price of heavy oils (U.S. Energy Information Administration April 1, 2021). This implies the costs associated with the production and upgrading of heavy oil are significantly higher than those associated with conventional oil production. In addition, due to the high concentration of hetero atoms (i.e., S and N) in heavy oil, their processing is very abrasive and leads to rapid equipment wear. The individual and collective effects of such factors largely determine heavy oil prices (Al-Yatama et al., 2018). Additionally, enterprises focusing on light oils will generate supernormal profits compared to their counterparts dealing in heavy oil, making the latter economically unviable unless new technologies are introduced to limit the overall cost of production (Ahmadi and Chen, 2020).

In general, the API gravity and sulfur content are the two main components used to determine the crude oil price. According to the Wang methodology, the price drops by $1.46 USD/bbl$ for every percent of sulfur content, while the price rises by $13.2 USD$ cent for each degree of API gravity increase. In addition, revenue, investment cost, operational cost, and profit were all carefully considered when evaluating the heavy oil upgrading process. As a result, the economic analysis revealed a profit advantage of $3.42 USD/barrel$ (Díaz-Boffelli et al., 2018).

4. Heavy oil composition and processing challenges

Unconventional heavy crude oils are a significant energy source that presents an opportunity for fossil fuel companies to provide an alternative for the depleting light oil resources and to respond to the energy demand of future generations. Heavy oil varies in composition and often displays a high content of high molecular weight hydrocarbons in addition to high levels of hetero compounds such as metals (nickel and vanadium), oxygen, nitrogen, and sulfur (Ahmadi and Chen, 2020). Heavy oils are rarely chemically homogenous, which explains the wide variation in their composition. A significant portion of the heavy oil molecules consists of asphaltenes, and resins, which have more than fifteen carbon atoms in the chain or in the form of an aromatic structure (Ahmadi and Chen, 2020; Ancheyta et al., 2005; Varfolomeev et al., 2023). Consequently, the composition and characteristics of heavy oils present several processing challenges.

Furthermore, this complex composition of hydrocarbon molecules present in heavy oil makes the refining process costly and complex (Patel et al., 2018; Varfolomeev et al., 2023). In addition, the high molecular weight compounds generate products with a low content of high-octane diesel and gasoline during processing. For this reason, heavy oils require additional efforts to guarantee their economic viability. Other unfavorable characteristics of heavy crude oils include the presence of an increased level of metal and heteroatom impurities, high sulfur content, high acidity, chemical complexity due to the high asphaltene content, low H/C ratio, low API gravity, and high viscosity.

The complex and heavy molecules of asphaltenes with low H/C ratios also present many technological challenges during processing, including heavy coking on catalysts (Davudov and Moghanloo, 2017). Further, impaired mobility of heavy oils resulting from the remarkably high viscosities significantly affects processing. Consequently, the processing of heavy oil includes taking measures to reduce the viscosity and drag. Carbon removal and hydrogen addition are two approaches for heavy oil upgrading that improve the processing of value-added products (Davudov and Moghanloo, 2017).

The challenges posed by the high content of asphaltene in heavy oil also extend to the upstream processes as the precipitation of active asphaltenes in the porous matrix, causes harmful pore plugging. Asphaltene precipitation in mechanical or chemical processes reduces the effective permeability of the liquid phase, thereby diminishing the recovery factor (Olsen and Ramzel, 1992). Therefore, it is crucial to find inhibitors to prevent or delay their precipitation or methods for the conversion of unwanted hydrocarbons. In-situ catalytic approach using nano-catalyst has been introduced. Due to the high surface area of nano-catalysts, they can adsorb asphaltene molecules and stabilize them in the oil phase with improved mobility (Guo et al., 2016). However, in-situ catalysis is still challenged by the possibility of catalyst retention in the formation (Varfolomeev et al., 2023). The injected of nano-catalyst or nanoparticles may aggregate larger particles or adsorb on the rock's surface, especially under severe temperature and pressure. Therefore, an ultra-dispersed suspension with high stability and selectivity should be prepared (Guo et al., 2016).

In addition, in the hydrotreating process of residual oil, asphaltenes are the primary source of coke and sediment solid material deposits, which significantly reduce the activity of the catalyst. Last, asphalt, being the heaviest and most complex component in heavy oil, is usually the most challenging fraction to process (Ancheyta et al., 2010; Temizel et al., 2018).

5. Heavy oil recovery technologies

Conventional refining unit operations are not very efficient for the transportation and refining of heavy oil due to its high viscosity, density, significant content of high-molecular components (asphaltenes and resins), heteroatoms (S, O, N), low H/C, as well as the presence of metallic impurities. Therefore, the thermal enhanced oil recovery technologies that can improve the heavy oil for conventional refining (Cyclic steam stimulation (CSS), Steam-assisted gravity drainage (SAGD), Steam Flooding method, and In-situ combustion (ISC)) are widely used to extract heavy and extra-heavy oil. The application of in situ combustions (ISC) process is regarded as one of the most promising strategies for heavy oil reservoirs. However, the cost-efficiency of this method, and its industrial-scale application are still limited. The In-situ combustion (ISC) consists of injecting air at high pressure into a reservoir to oxidize a small portion of hydrocarbons in situ that serve as fuels. During this process, the viscosity of the oil is significantly reduced to allow the flow of the heavy oil through porous media (Moore et al., 1995, Yannimaras and Tiffin, 1995; (Moore et al., 1995, Yannimaras and Tiffin, 1995; Veliyev et al., 2023). As shown in Fig. 4**,** the oil is pumped and transported towards the production wells with the help of a vigorous drive of flue gases, steam, and hot water. The success of an ISC process mainly depends on the combustion front stability and its rapid propagation. This combustion is due to the injection of oxygen, which ignites when in contact with the oil (Moore et al., 1995, Yannimaras and Tiffin, 1995). Also, oil from the combustion zone is upgraded in situ as the heaviest components burn and the lighter crude oil components evaporate ahead of the combustion front (Zhang et al., 2013). The adoption of the ISC technology can lead to cracking of hydrocarbons, vaporization of light hydrocarbons and water, while the heaviest hydrocarbons form depositions. This outcome depends on the kind of oxidation reaction that takes place, which differ in mechanism as well, based on the temperature. These reactions include low-temperature oxidation (LTO)

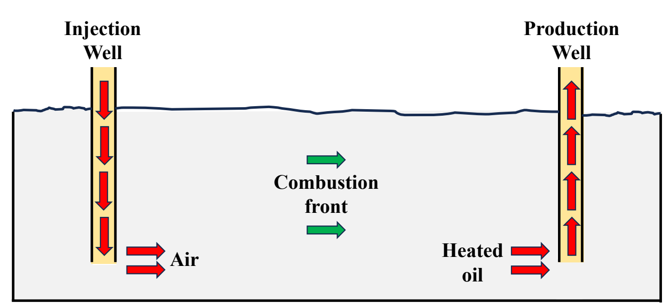

Fig. 4. Schematic illustration of In-Situ Combustion (ISC) process for heavy oil recovery (Turta et al., 2007).

reactions, medium-temperature oxidation (MTO) reactions and high-temperature oxidation (HTO) reactions (Santos et al., 2014).

Cyclic Steam Stimulation (CSS) is another thermal technology that is knows as a "huff and puff" process which occurs in three steps (Fig. 5). In the first step, steam is injected directly into the crude reservoirs at high temperature and pressure for an extended period of several weeks (Guo et al., 2016). In a subsequent "soak step", the distribution of the injected steam is enhanced by the diffusion of hot water. Then, the injection is stopped to allow for the saturation and the distribution of heat in the reservoirs and eventually the thinning of the formation and the improvement of the mobility of the oil. In the third step, the injector well is used as a producer well for the recovery of the oil from the reservoir. The recovery rate of the CSS technique is between 20% and 40% OIP (Oil In Place) (Santos et al., 2014).

As for the Steam Flooding (SF) method, the injection of the steam in vertical injection wells is continuous and non-uniform, unlike the CSS technique. The steam injection with this method is focused on creating a pattern of hot zones, which leads to the formation of a zone of condensed water between the injected steam and the oil, as shown in Fig. 6. The formation of this condensed zone drives the oil towards the production wells, after its viscosity has been reduced due to the increasing temperature (Guo et al., 2016). The recovery rate in the production wells is 60% Oil In Place (OIP) (Santos et al., 2014).

The Steam Assisted Gravity Drainage (SAGD) recovery process can reach rates of up to 70% OIP and since its invention in 1970, it has been considered the most essential technology for the in-situ recovery of heavy oil. As shown in Fig. 7, this technology consists of two horizontal wells that are vertically aligned. The steam is injected in the upper well, while the oil flows down in the lower well, due to the effect of gravity after its viscosity has been reduced (Santos et al., 2014). Some of the limitations of this technique are the high quantity of water that is required and its limited applicability depending on the geology and geometry of the reservoir (Guo et al., 2016).

Other thermal enhanced oil recovery technologies include downhole steam generation, electric heating, electromagnetic heating, and microwave techniques. The downhole steam generation technique involves the generation of the steam that is necessary for the reduction of the oil viscosity down in the hole, where a fuel burner ignites the oxidizing gas and fuel (Eson, 1982). Water is injected in the burner in direct contact with the combustion gas and hence, steam is released (Eson, 1982). On the other hand, electric heating and electromagnetic heating techniques are based on lowering the oil viscosity by heat that is generated using electric currents or by formation resistive heating (electro-magnetic heating) (Das, 2008, Rodriguez et al., 2008). Microwave heating assisted gravity drainage is another technique that is being developed to replace steam with heat that is generated using microwave radiation (Hascakir et al., 2008). However, compared to the conventional thermal processes, these technologies are yet to prove their technical ability and economic feasibility (Santos et al., 2014).

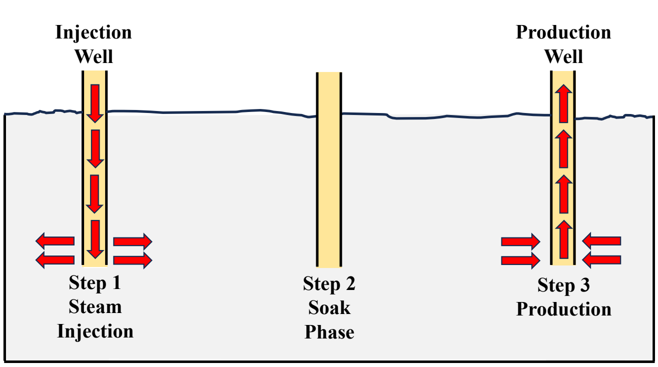

Fig. 5. Schematic illustration of Cyclic Steam Stimulation (CSS) (Shah et al., 2010).

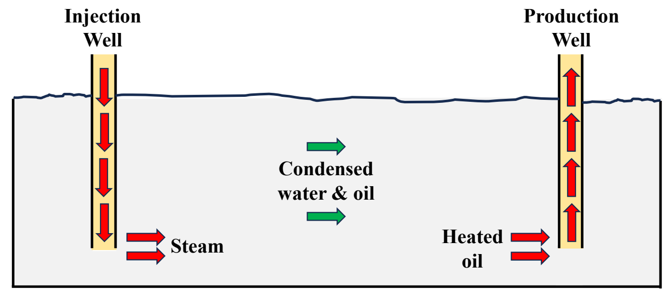

Fig. 6. Schematic illustration of steam flooding (SF) (Guo et al., 2016).

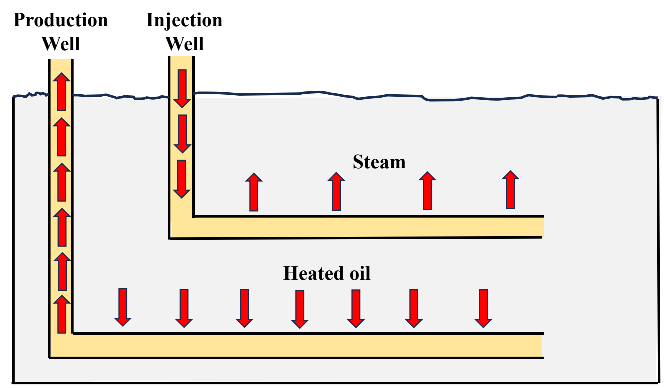

Fig. 7. Schematic illustration of Steam Assisted Gravity Drainage (SAGD) process for heavy oil recovery (Elliott and Kovscek, 1999).

Chemical processes for the recovery of heavy oil exist but are not usually employed due to their economical non-viability. These processes include surfactant flooding, polymer flooding, alkaline surfactant polymer flooding and solvent flooding (Guo et al., 2016). Surfactant flooding includes the injection of an aqueous fluid containing a surfactant, with the objective of creating oil-in-water emulsions for the recovery of oil (Fletcher et al., 2015). Polymer flooding consists of injecting a high molecular weight (high inherent viscosity) polymer into the water phase to decrease its mobility and hence favor the mobility of the oil phase (Fletcher et al., 2012). Meanwhile, the Alkaline surfactant polymer process includes the injection of both a surfactant and a polymer, in addition of an alkaline that reacts with hydrocarbons in heavy oil to form in-situ natural surfactants (Sheng, 2013). The effects of the surfactants lower the interfacial tension between the water and oil phase, while the polymer increases the viscosity of the water, favoring the displacement of the oil phase instead (Sheng, 2013, Guo et al., 2016). Solvent flooding processes include the injection of miscible solvents, either with steam or alone in the form of a slug or as a vapor (Guo et al., 2016). Table 2 summarizes the main findings of heavy oil recovery technologies.

6. Heavy oil as feed for refinery

Refining medium and heavy oil poses economic and technical challenges that directly affect the yield of the refineries. This challenge arises against the backdrop that all three components—production, transportation, and refining—must achieve an adequate rate of return for investing companies, whether as individual units for horizontally integrated companies or vertically integrated ones (Olsen and Ramzel, 1992). In addition, this investment must compete with international opportunities for investment in the petroleum industry and other sectors. The complex nature of heavy oil characterized by high viscosity, low H/C ratio, and a high content of asphaltene, sulfur, nitrogen, and metals, makes this endeavor challenging. consequently, there are

Table 2
Summarizing the heavy oil recovery technologies.

Technology	Key Features	Recovery Rate for Oil in Place (OIP)
Cyclic Steam Stimulation (CSS)	"Huff and puff" process with steam injection and soak step	20 % – 40 %
Steam Flooding	Continuous non-uniform steam injection to create hot zone	60 %
Steam Assisted Gravity Drainage (SAGD)	Two vertically aligned wells with steam injection	Up to 70 %
Downhole Steam Generation	Steam generation in the well through fuel burner	Viscosity reduction
Electric and Electromagnetic Heating	Heat generation using electric currents or resistive heating	Viscosity reduction
Microwave Heating Assisted Gravity Drainage	Heat generated using microwave radiation	Under development, feasibility not proven
Surfactant Flooding	Injection of surfactant for oil-in-water emulsions	Economically non-viable
Polymer Flooding	Injection of high molecule weight polymer	Economically non-viable
Alkaline Surfactant Polymer Flooding	Injection of surfactant, polymer, and alkaline	Economically non-viable
Solvent Flooding	Injection of miscible solvents, alone or with steam	Economically non-viable

obstacles hindering the upgrading of heavy crude oil and affecting its marketability. First, due to the high carbon content of heavy oil, it not only yields lower energy output compared to light crude oil but also poses greater environmental damage, releasing more carbon dioxide emissions upon burning (Marafi et al., 2019). Therefore, hydroprocessing of heavy oil is necessary in order to increase the hydrogen, enhance energy output and limit greenhouse gas emission. However, the complex nature of the feedstock of heavy oil makes process selection and implementation difficult, which is why, based on the composition of the feedstock, correct choices should be made for the catalyst types, systems process configuration and mode of operation. Processes like hydrocracking and hydrotreatment of heavy oil enable the reduction of the sulfur content in heavy oil that is often medium sour crude and sour crude because of its high sulfur content ($>$ 1%), correlating with the low API gravity of heavy crude. Sulfur elimination is not confined to heavy oil but also extends to light and medium crude, with the aim of obtaining products that meet the stringent regulations related to the weight ratio of sulfur in fossil fuel. However, higher sulfur content in the oil leads the lower refining efficiency. This is due to the sulfur causing corrosion in refinery equipment, deactivation of the catalysts and an increased air pollution (Marafi et al., 2019; (Marafi et al., 2019; Chehadeh et al., 2023).

Furthermore, the organic nitrogen compounds present in crude oil exhibit a similar correlation with the API gravity as the sulfur compounds. The same correlation is observed for other hetero-atoms such as metals (Nickel (Ni) and Vanadium (V)), organic salts and inorganic salts, significantly contributing to the low gravity of the heavy oil. To remove inorganic salts, a desalting process is employed before distillation. Asphaltenes, resins, and Conradson carbon residue (CCR) are particularly detrimental to processing equipment. They contribute to catalyst deactivation, and their precipitation leads to severe pressure drops, thereby increasing the energy requirements for oil flow (Marafi et al., 2019; Rana et al., 2021; AlHumaidan et al., 2024).

7. Refinery integration

Refineries have been usually standalone, where the crude oil is upgraded to produce conventional fuel products. However, the new approach of the refinery integration, which consists of the utilizing heavy oil, its waste oil, and by-products to produce petrochemicals by the integration of chemical processes. This integration of the refineries and petrochemical complexes provides production of high-value petrochemicals and this is often an economical approach that improves the cost-efficiency of heavy oil production and conversion (Al-Samhan et al., 2022). Integration of the refineries and petrochemical complexes marks the end of the downstream processes and the begging of upstream operations. The integration provides essential benefits compared to standalone refineries (Ancheyta, 2016). Standalone refineries face market pressures due to crude price volatility, global product specifications, and demand swings. Integrated refineries are well placed to accommodate future product patterns (Manara et al., 2018).

According to most experts, future petroleum supplies are expected to include heavier materials as a significant portion of incremental demand will have to come from heavier crudes at current consumption growth rates (Zyrin and Ilinova, 2016). On the other hand, newer discoveries favour lighter crudes associated with deeper production zones. However, this does not exclude the need for heavy crude producers, such as Mexico and Venezuela, to transfer their products into the market (Swaty et al., 2002). The vastest heavy oil reserves are found in the North American/Caribbean region and the use of these resources will be crucial in the effort to respond to future energy demand. Nonetheless, due to the difficulty of marketing heavy oil and the price volatility of crude oil, integrated refineries and petrochemical complexes are becoming a necessity for improving the economic profit originating from the processing of crude oil. The economics of integrated facilities, however, are complex and many possible configurations are available.

Increased usage of heavy crude offsets conventional crude supply, necessitating considerable adjustments in refining operations. However, the trend may differ in North America, where unconventional crude or so-called light tight oil (LTO) is used (Shui et al., 1997). The light hydrocarbons are separated on-site and fed to the petrochemical sector as a feedstock. The depletion of conventional crude oil, on the other hand, forces refiners to turn to heavy crude oil production and processing as a direct crude oil upgrading option. In addition, refinery-petrochemical integration and direct conversion of heavier crude to chemicals (CtC) and building block polymers improves the petrochemical production (Shui et al., 1997).

Integrating existing refineries (state-of-the-art technology and refining flexibility) with significant alterations, depending on the heavy feedstock and fossil fuel demand in petrochemical, is an advanced trend in refinery processing. The integration process is chosen based on the crude oil composition or the requirements for petrochemical products. In the refining sector, a combination of thermal and catalytic processes can be employed as primary conversion processes to achieve optimal fossil fuel use. Chemical and petrochemical feed such as syngas (CO,CO_2, H_2) and olefins (ethylene, propylene, and butenes) are produced using traditional thermal and catalytic processes (Bhatia and Sharma, 2006). Currently, the enabling technologies for converting crude and residual to petrochemicals as mentioned earlier are steam cracking, gasification, catalytic cracking, while the feed type, and product demand primarily determine the process choice (Lin, 2000). The gasification process produces syngas, while thermal cracking and catalytic cracking produce olefins, aromatics (benzene, toluene, and xylene) and fuel gas (methane, propane, ethane, etc). The olefins production yield using these two processes is highly dependent on temperature for both these processes, while the catalysts type and properties can be of considerable influencing as well, especially for heavy crude. The typical commodity products that are based on the chemicals obtained through refinery integration include textile, plastic and detergents for aromatics, and rubber, plastic, and a variety of polymers for olefins.

The composition of the crude oil, its API gravity and the content of impurities weigh heavy on the selection of the upgrading process. Subsequently, the nature of the integration and the yield of the production of the chemicals is affected as each of these processes has its distinct qualities, intricacies, and limitations (Al-Samhan et al., 2022).

Table 3
Some Patents literature of heavy oil processing.

Inventors	Title of Patent	Patent Number	Date of Patent	Invention Patent Country
Thompson et al., 1959	Heavy oil conversion process	2873245	1959	United States
Mills, 1964	Catalytic hydrocracking	3131142	1964	United States
Gatsis and Gleim, 1971	Multiple-stage slurry processing for black oil conversion	3622495	1971	United States
Oleck et al., 1975	Process for demetalizing and desulfurizing residual oil with hydrogen and alumina-supported catalyst	3891541	1975	United States
Hopkins et al., 1978	Large-Pore hydrodemetallization catalyst and process employing same	4119531	1978	United States
Bearden, Jr et al., 1979	Hydroconversion of heavy hydrocarbon	4134825	1979	United States
Allan et al., 1979	Staged slurry hydroconversion process	4151070	1979	United States
Fisher et al., 1981	Process for upgrading heavy hydrocarbonaceous oils	4294686	1981	United States
Olmstead, 1984	Enhanced removal of nitrogen and sulfur from oil-shale	4431511	1984	United States
Garg, 1986	Hydroconversion of heavy oils	4606809	1986	United States
de Agudelo et al., 1989	Catalyst for the simultaneous hydrodemetallization and hydroconversion of heavy hydrocarbon feedstocks	4832829	1989	United States
Brown et al., 1989	Process for demetallizing and desulfurizing heavy crude oil	4885080	1989	United States
Cha et al., 1991	Process for removing heavy metal compounds from heavy crude oil	5041209	1991	United States
MacWilliams et al., 1992	Process and apparatus for partial upgrading of a heavy oil feedstock	5110447	1992	United States
Simpson et al., 1993	Resid hydroprocessing catalyst	5210061	1993	United States
Schuker, 2003	Heavy oil upgrading process	US 6524469 B1	2003	United States
Chen et al., 2007	Process for upgrading heavy oil using a highly active slurry catalyst composition	US2006/ 0054535 A1	2006	United States
Stepanik et al.,2007	Method of upgrading a heavy oil feedstock	US2007/ 0284285 A1	2007	United States
Dillon et al., 2013	Hydrodemetallization catalyst and process	US2010/ 0084311 A1	2010	United states
Latimer, 2010	Process for producing heavy oil	US 7779914 B2	2010	United states
Rayo et al., 2011	Catalyst for the hydrodesulfurization of residua and heavy crudes	US 2011/ 021897 A1	2011	United States
Chornet and Chornet, 2012	Process for treating heavy oils	US 8105480 B2	2012	United States
Al-Sheikhly et al., 2013	Radiation processing of heavy oils	US 8470166 B2	2013	United States
Dillon et al., 2013	Hydrodemetallization catalyst and process	US 8563456 B2	2013	United States
Chornet et al., 2014	Process for treating heavy oils	US 8871081 B2	2014	United States
Rana, et al., 2015	Catalyst for the first hydrodemetalization step in a hydroprocessing system with multiple reactors for the improvement of heavy and extra heavy crudes	US 9133401	2015	United state
Zhao et al., 2016	Integrated process for upgrading heavy oil	US 9290706 B2	2016	United States
Rana, et al., 2016.	Mild acidic catalyst for hydroprocessing of heavy crude oil and residue and its synthesis procedure. U.S. Patent	US 9387466 B2	2016	United state
Ancheyta et al., 2018	Hydroconversion process to upgrade the transport properties of heavy oil and extra-heavy crude oils at low severity conditions using dispersed-phase catalyst	US 2016/ 0362615 A1	2018	United States
Rana,et al., 2018	Catalyst for mild-hydrocracking of residual oil	.S. Patent 9919293	2018	United state
Rana and Alhumaidan, 2018)	Hydrodemetallization catalysts	US 9861972 B1	2018	United States
Plecha et al., 2019	Spheroidal resid hydrodemetallation catalyst	US 10279335 B2	2019	United States
Abbaslou et al., 2019	Process for partial upgrading of heavy oil	US 10358610 B2	2019	United States
Klussmann et al., 2019	Heavy marine fuel oil composition	US 2020/ 0199463 A1	2020	United States
Shaik et al., 2020	System and methods for processing heavy oils by oil upgrading followed distillation	US 10696910 B2	2020	United States
Hodgkins et al., 2020	Method to improve the efficiency of pipeline transportation of heavy oils	US 10851314 B2	2020	United States
Farmer et al., 2021	Treatment for upgrading heavy crude oil	US 10907106 B2	2021	United States
Patino, 2021	Methods for enhancing heavy oil recovery	US 10907105 B2	2021	United States
Ai-Herz et al., 2021	Methods including direct hydroprocessing and high- severity fluidized catalytic cracking for processing crude oil	US 10954457 B2	2021	United States
Fathi et al., 2022	Process for heavy oil upgrading utilizing hydrogen and water	US 11286429 B2	2022	United States
Choi et al., 2022	Processes for thermal upgrading of heavy oils utilizing disulfide oil	US 11306263 B1	2022	United States
Koseoglu, 2022	Multi-step pressure cascaded hydrocracking process	US 11326111 B2	2022	United States

Due to the high activity of zeolite catalysts, the application of zeolite-based catalysts has gained traction in recent years (Li et al., 2011). However, in heavy feedstock, zeolite catalyst topology and pore accessibility become critical; consequently, zeolite catalysts with increased porosity improve feed diffusion and stability regarding deactivation. Furthermore, shape-selective molecular cracking and increased product yield are highly demanded and the current petrochemical integration projects are focused on enhancing and expanding the current technologies in order to meet these objectives (Xu et al., 2009). The refineries should also have enough flexibility to process a variety of feedstocks while also buffering against market volatility. As a result, more petrochemical projects are anticipated to be integrated with existing refineries in the future, ensuring long-term competitiveness and commercial sustainability (Al-Samhan et al., 2022).

8. Heavy oil processing technologies

Process technologies are essential in heavy oil refining. Oil distillation is one process that enables the subsequent processes to obtain various marketable products. (Zyrin and Ilinova, 2016). There is a range of technologies and equipment inside a heavy oil refinery and different systems have been developed to enable real-time digital technology to identify and respond to issues related to the performance of these refineries. Table 3 shows some patents literature related to heavy oil processing since the 1950 s. These patents describe new technologies for the conversion of crude oil and enhancements to older technologies to overcome challenges related to the crude oil becoming heavier with time and increased exploitation.

8.1. Refining processes of residue and heavy compounds

In order to overcome all of the difficulties that accompany the upgrading of heavy oil, a delicate process selection for the separation, conversion and treatment of heavy oil in refineries is required (Rana et al., 2008), which are outlined as follows.

8.1.1. Non-catalytic refining processes of residue

Solvent deasphalting, gasification, delayed coking, fluid coking, flexicoking and visbreaking are the most widely used non-catalytic separation processes, particularly for the elimination of residue (Rana et al., 2007). A summary of these processes is as follows.

8.1.1.1. Solvent deasphalting (SDA). Solvent deasphalting (SDA) is a non-catalytic separation process in which a light paraffinic solvent is used to eliminate resin-asphaltene substances and polycyclic aromatic hydrocarbons from the oil, producing low contaminant deasphalted oil (DAO). This separation is based on the difference in density (molecular weight) between the asphaltene and the light hydrocarbons present in heavy oil (Rana et al., 2007). The most widely used solvents in solvent deasphalting are propane, n-butane, isobutene, pentane, and their mixtures. The composition of the solvent used is critical for the yield of the separation and the quality of the DAO, with propane providing the highest separation yield but a mediocre DAO quality (Rana et al., 2007, Sun and Meng, 2020; Matsushita, 2023). As shown in Fig. 8, this separation occurs in an extractor, where finding the optimal settings of the temperature, pressure and the amount of solvent is vital and depends on the composition of the solvent as well. SDA has proven to be an efficient preliminary refining step of heavy oil, reducing the cost, and improving the performance of the subsequent processes (Rana et al., 2007, Magomedov et al., 2019).

During crude oil refining, the refineries produce a considerable amount of oily sludge. This sludge comprises asphaltene, sediment sludge, chemical components such as substituted benzenes, or aromatic hydrocarbons, polycyclic aromatic hydrocarbons. and other harmful and poisonous chemicals, which are categorized as hazardous waste. To prevent or at least limit the contamination of the environment due to the release of these substances, rapid detection of any leakage and immediate intervention are required. The oily sludge fuel processing technology provides a new route for not only the disposal of oily sludge, but its upgrading and usage as a fuel source (Raut et al., 2013). A new combined process of atmospheric flash evaporation with solvent deasphalting was initiated as a way forward for oily sludge treatment. According to Ning et al. (Ning et al., 2015), isopentane solvent at temperature ($175^{\circ}C$), pressure ($3.7MPa$), and solvent volume ratio of 5 are considered as the optimum operating conditions of the solvent deasphalting process.

8.1.1.2. Thermal processes for refining heavy oil residue. Gasification is a thermal process that produces syngas, carbon black and ash by complete cracking of the residue using steam and injected oxygen at a high temperature 1000°C or greater (Steinberg and Cheng, 1989, Rana et al., 2007). Elevated pressures are preferred for the gasification process due to the high energy consumption of the subsequent compression of the hydrogen and syngas produced, even though the gasification can still be carried out at near atmospheric pressure (Steinberg and Cheng, 1989). As shown in Fig. 9, various subsequent processes are used for the separation and recovery of the products that emanate from the gasifier. Integrated gasification combined cycle (IGCC) is an advanced gasification technology that is used to produce syngas and pressurized gas from carbon-based fuels such as coal, biomass, and refinery bottom residues. The produced gases are then cleaned and used to produce electrical power. IGCC has showed great potential in producing cleaner syngas (Di Gianfrancesco, 2017). Delayed coking is another thermal cracking process that converts the petroleum bottom of the barrel (residua) into gas and liquid products (naphtha and diesel), with coke as a by-product. The thermal cracking temperatures in this process are between $485 and 505^{\circ}$C, with a short residence time in the coker furnace tubes, which delays the coking of the feed residua until it reaches the coke drums (Fig. 10). Delayed coking is the most widely used crude oil upgrading technology because it is a batch-continuous process with inherent flexibility and low-cost of operation (Ellis et al., 1998, Sawarkar et al., 2007). Fluid coking, also called fluidized-bed coking, is a thermal process that was developed by Exxon for the conversion of heavy feedstock to lighter and more valuable products (Chrones and Germain, 1989, Speight, 2013). This process consists of a fluidized bed of coke particles that is sprayed with large volumes of the liquid feed via nozzles that are driven by steam injection. A portion of the coke is burned in a heater to provide the necessary heat for the coking which takes place on the surface of the coke particles in the reactor at temperatures of $510-550^{\circ}$C (Fig. 11) (Speight, 2013, Gray, 2015). This process allows for higher yield of valuable products, lower yields of coke at a shorter contact time than delayed coking (Speight, 2013). Flexicoking is a descendant of the fluid coking process, with the addition of a gasification reactor for the conversion of coke into low heating value gas (Speight, 2013, Gray, 2015). The addition of the gasifier can allow the conversion of up to 97% of the coke at a temperature between 830 and 1000 °C, which is maintained by the injection of steam (Fig. 12). However, the yield of the liquid products is the same as the yield obtained with fluid coking as the same reactor is used (Speight, 2013). A relatively more recent and mature thermal process for upgrading heavy oil is viscosity-breaking (visbreaking). This process consists, as its name suggests, on reducing the viscosity of the feed material to facilitate its flow (Speight, 2013, Gray, 2015). In refineries, this mild thermal cracking process is used to convert high viscosity residua to lighter oil (Gray, 2015). The feed material is heated up to a temperature of $455-510^{\circ}$C in a furnace at a short residence time and under an outlet pressure of $0.34-2.07MPa$. After the visbreaking reactions are completed, the cracked products are separated in a flash-distillation chamber (Fig. 13). Subsequently, Naphtha and light gas oil are produced by fractionating the overhead material from the flash chamber, while the liquid products are used to produce heavy gas oil distillate and a feedstock of low viscosity, in a vacuum fractionator (Speight, 2013).

8.1.2. Catalytic hydroconversion of residue

Among all the commercially available processes for transforming heavy oils, catalytic hydro processing is one of the most auspicious technologies. The addition of the catalysts used in hydro-processing serves the function of breaking the bonds in the functional groups $C-O$, $C-N$ and $C-S$. This is done for the purpose of rearranging and restructuring the hydrocarbons present in the heavy oil in order to obtain lighter oil. Consequently, the viscosity of the heavy oil is effectively reduced, the chemical properties of the oil are enhanced, and liquid flow of the oil is promoted (Jia et al., 2016). To create the needed high-quality transportation fuels, residual upgrading or extra-heavy crude processing is required as mentioned earlier (Weiss and Schmalfeld, 1999; Vakhin et al., 2023). As a result, refineries are making a continuous effort to upgrade their technologies to handle this heavy feedstock with low API gravity. With the upgrading of the refineries,

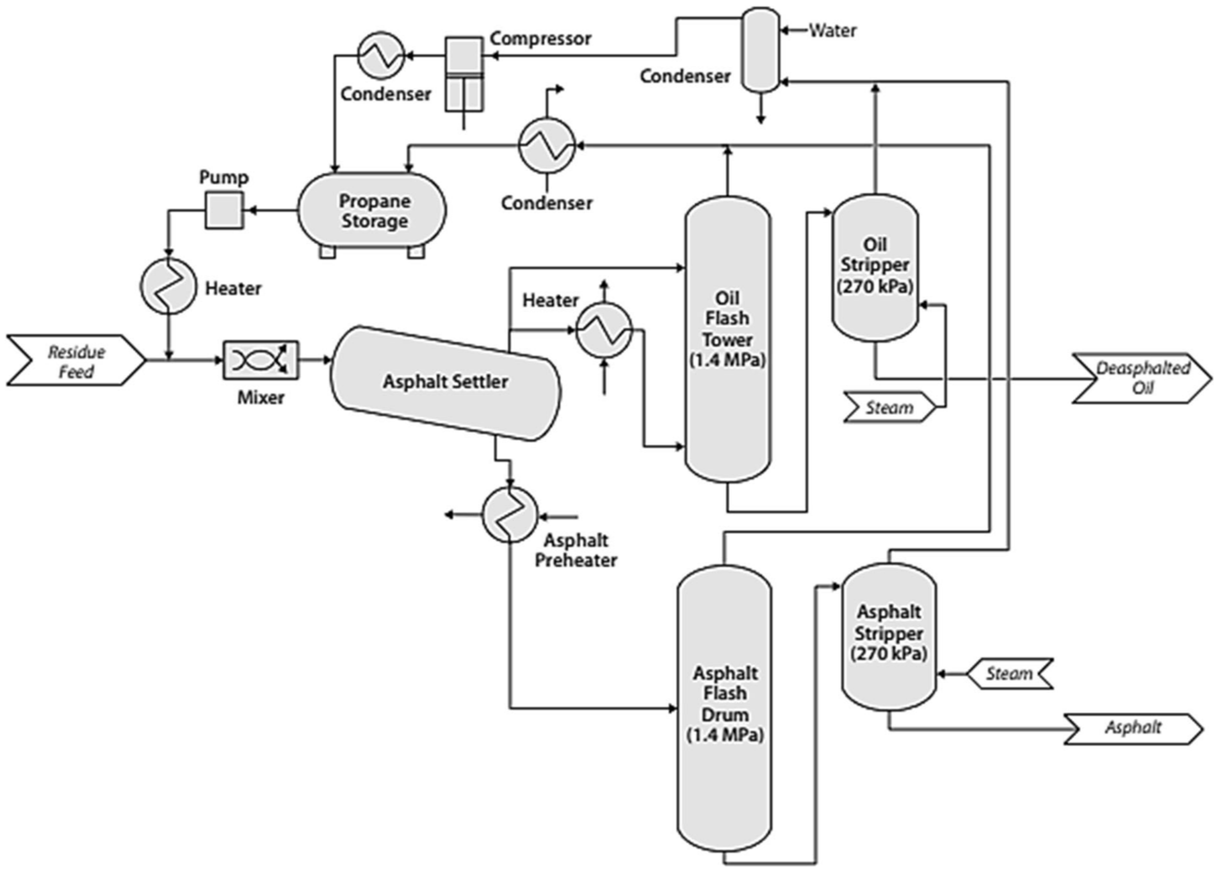

Fig. 8. Schematic of solvent deasphalting process (Gray, 2015).

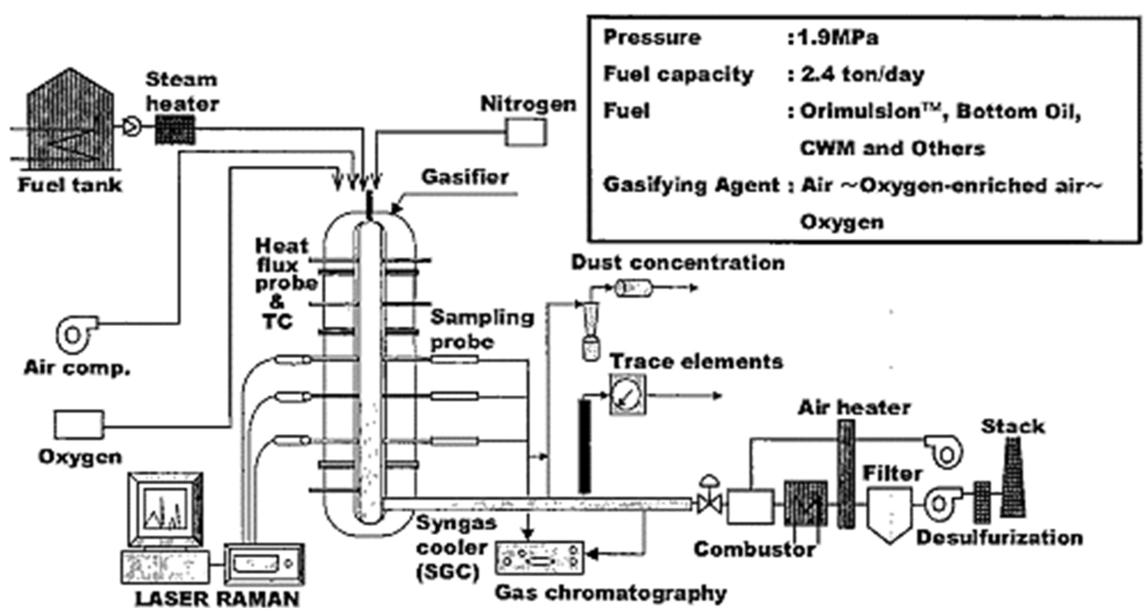

Fig. 9. Schematic diagram of gasifier (Kidoguchi et al., 2002).

heavy oil shall present an enticing alternative to light oil, especially with its availability in high abundance. However, these abundant heavy oil reservoirs come with their own set of challenges as discussed above, including high viscosity at operating temperatures and high concentrations of asphaltenes, sulfur, nitrogen, and heavy metals such as Vanadium (*V*) and Nickel (*Ni*) (Speight, 2006).

The restructuring of the high molecular weight of the hydrocarbons present in heavy oil is essential for the reduction of the density and viscosity of the oil. This is a challenge that prevents the exploitation of heavy oil due to the limitation of conventional recovery technologies. To overcome this difficulty, the adoption of catalytic hydroconversion processes is necessary in order to produce high-value products from heavy oil (Li et al., 2013).

For the catalytic hydroconversion of heavy oil residue, fluid catalytic

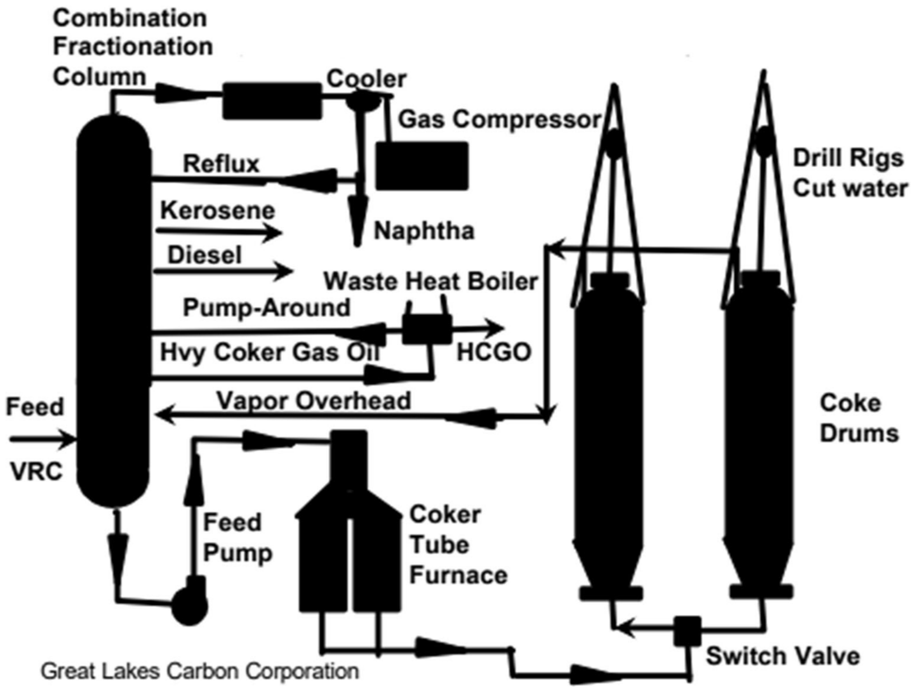

Fig. 10. Schematic flow diagram of delayed coking process (Ellis et al., 1998).

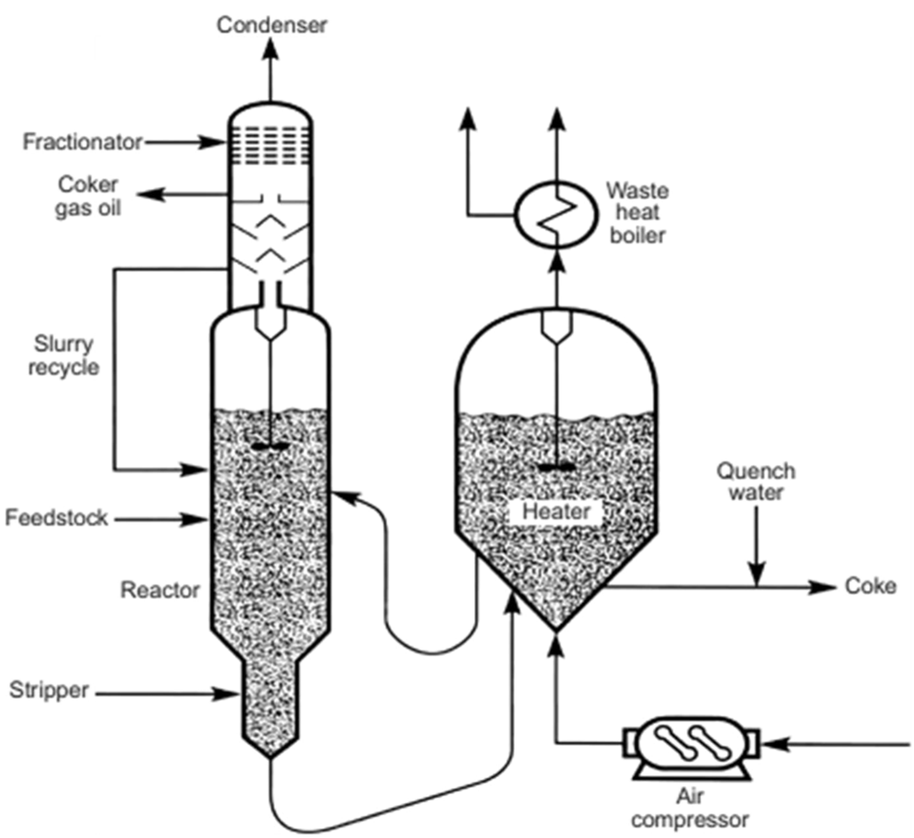

Fig. 11. Schematic illustration of a Fluid Coker (Speight, 2013).

cracking process (RFCC) and hydroprocessing are the most widely used technologies. RFCC consists of hydrocracking the hydrocarbons using finely powdered zeolite-based catalysts that are in movement in the circulating fluid-bed reactor (Otterstedt et al., 1986, Gray, 2015). This movement is due to the fine size of the catalyst particles, which behave like a fluid when air or hydrocarbon vapor are injected in the reactor. The temperature in the reactor is maintained at 470 –565 °C, while the feed material is vaporized before reaching the reactor due to contact with heated catalysts that is coming from the regenerator. This contact occurs during the concurrent up-flow of both the feedstock and the

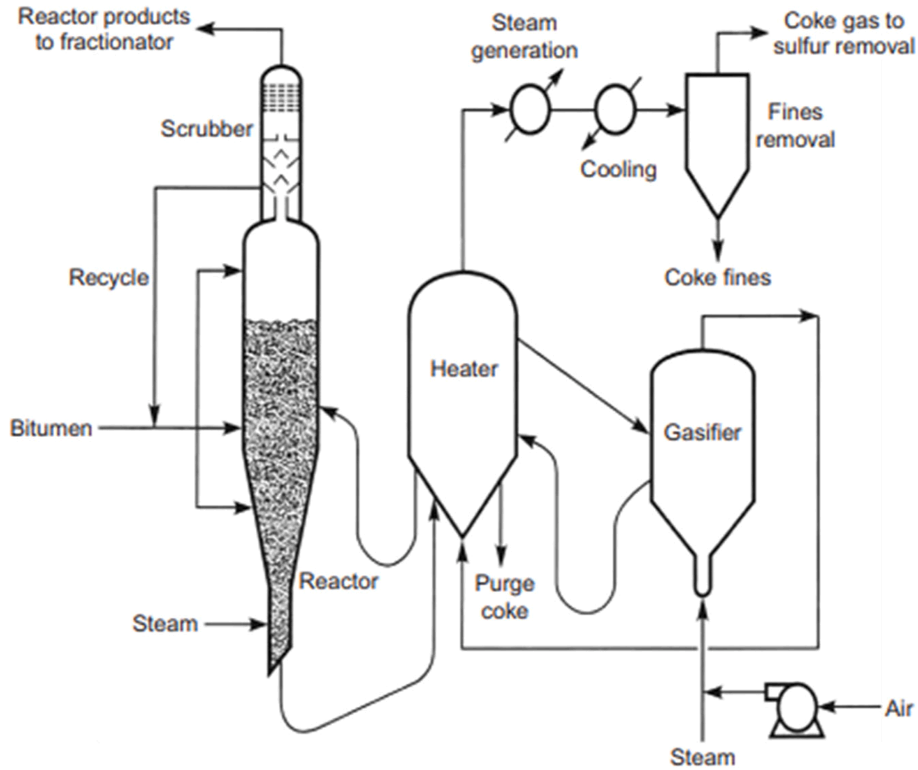

Fig. 12. Schematic illustration of the flexicoking process (Speight, 2020).

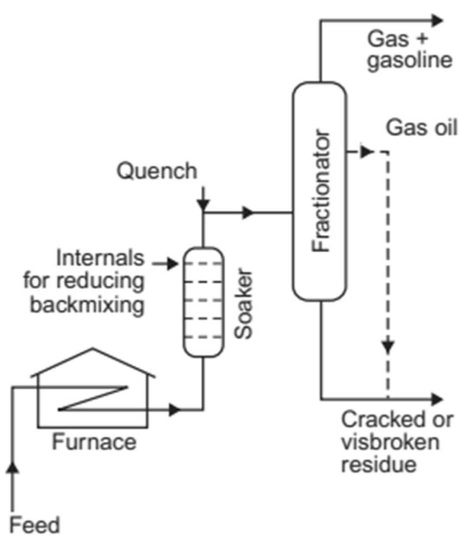

Fig. 13. Schematic illustration of the visbreaking process (Speight, 2013).

catalysts which are burned in the regenerator in order to eliminate the coke that contaminates the surface of the catalysts and deactivates them (Fig. 14). The pressure is maintained at approximately $0.11MPa$, with a feedstock/catalyst ratio ranging from 3:1 to 50:1. Volume conversion rates of as high as 70% of the residua have been achieved (Speight, 2013). In contrast to RFCC, the catalysts used in fixed-bed hydro-processing are arranged in several drums that are called converters, where the catalysts are placed in layers. Like in RFCC, these catalysts, which are shaped as small pellets, are burned with air in a regenerator to remove the accumulated coke (Fig. 14). The typical temperature for the evaporation of the feedstock in the converter is maintained at $450^{\circ}C$ with a pressure that ranges from 0.05 to $0.10psi$. This process is now outdated and, in most cases, replaced by RFCC (Speight, 2013, Gray, 2015).

Fig. 15 elucidates the process choice for the hydro-conversion of heavy oil based on the API gravity, Cradson carbon residue (CCR) and content of sulfur and metal impurities (Rana et al., 2007). From Fig. 15, we can tell that the choice of the hydro conversion process is highly dependent on the content of the heavy oil. It shows that the residue fluid catalytic cracking process (RFCC) can only be used when the content of the impurities (Ni, V) is low, while hydro processing conversion can be used for medium to high impurities content and at medium asphaltene and CCR ratios. Large impurities in the feedstock can be handled by thermal processing, but this process produces several undesirable by-products (Marafi et al., 2019).

For the enhancement of these hydro-conversion processes, technological advancements, especially in relation to the properties of the catalysts and their operating conditions are necessary (Marafi et al., 2019).

8.1.3. *Catalytic heavy oil hydrotreating processes*

As previously stated, there are considerable variations between light and heavy crudes (Temizel et al., 2018; Marafi et al., 2019; Rana et al., 2020). Metals and asphaltenes are more abundant in the latter. To transform such heavy molecules, the catalysts should contain several pores to allow the diffusion of the molecules to the catalytic sites. On the other hand, the specific activity of these catalytic sites is reduced when the catalysts porosity is high, and this is due to the decrease of the surface area. Large surface areas provide more area for the reactions to take place and hence higher reaction yield are obtained, which is the case for light crude oil. For heavy feeds, on the other hand, appropriate porosity is critical for allowing the intra-diffusion of large molecules, extending the life of the catalyst and for enlarging the metal-retaining capacity of the catalyst. This is due to the large metal depositions and the coking byproducts that are far more abundant in heavy oil, compared to light oil. As a result, if sufficient catalytic activity is achieved, the textural characteristics of the catalysts can have a more significant role than the chemical composition and surface area (Dong

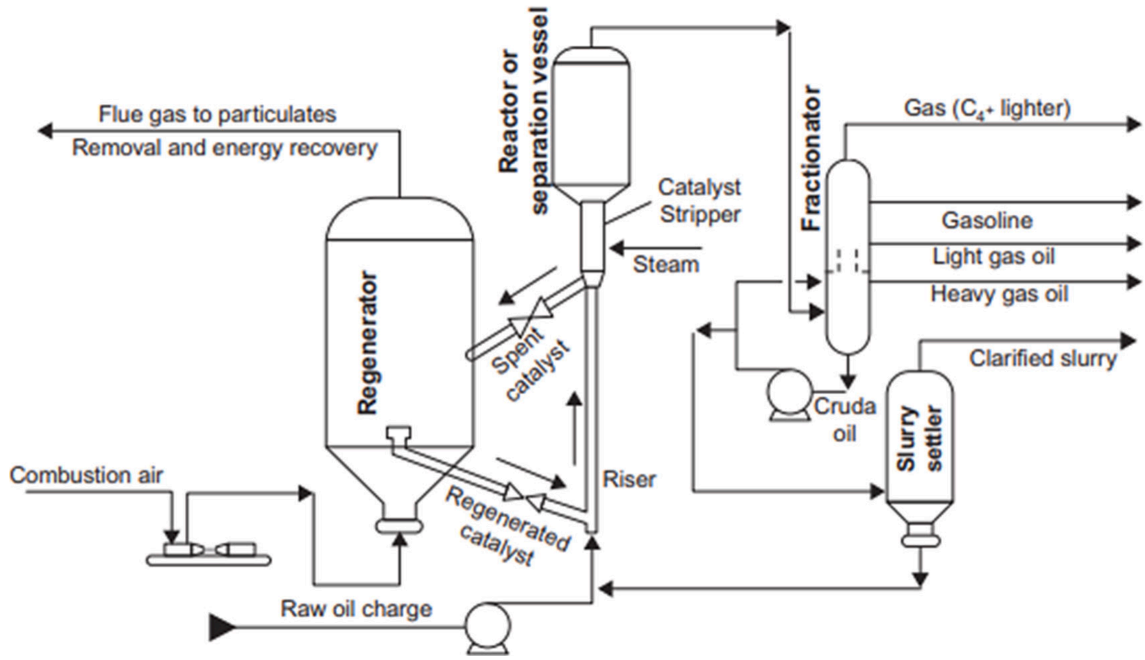

Fig. 14. Schematic illustration of a RFCC reactor.

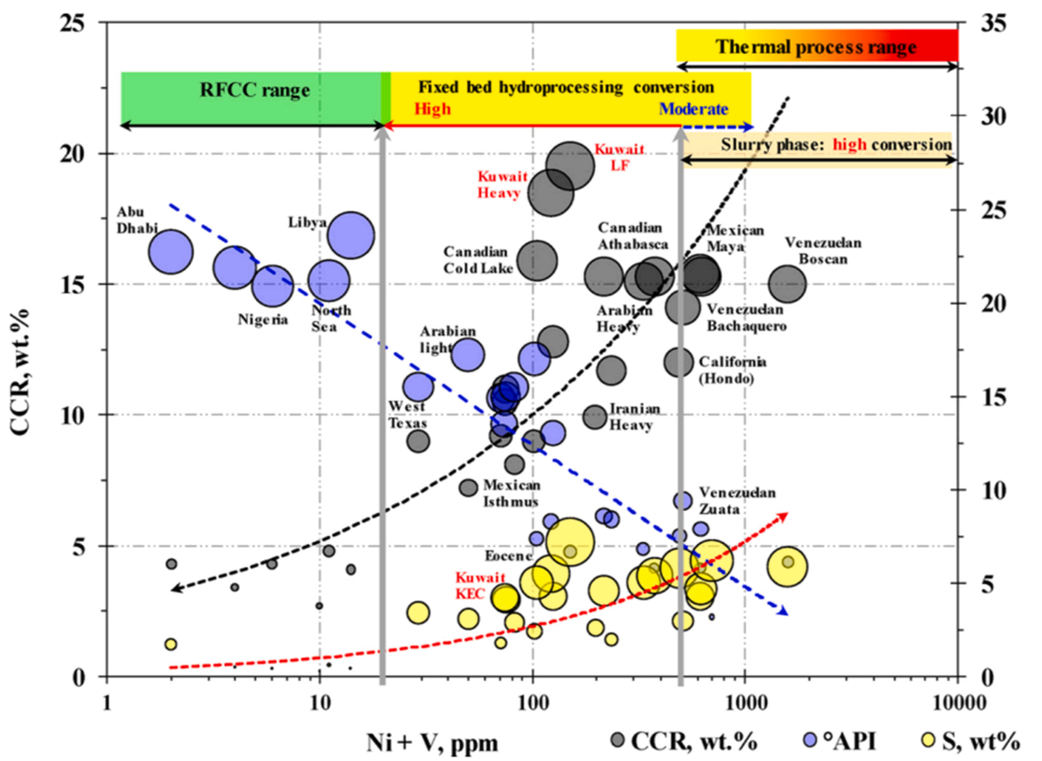

Fig. 15. Process choice for hydro conversion of heavy oil based on the API gravity, CCR, sulfur content and impurities (Rana et al., 2007, Marafi et al., 2019).

et al., 2019; Rana et al., 2020; Noskov, 2023; Vorobyeva et al., 2023).

Furthermore, the efficiency of active ingredient utilization can be increased by the dispersion of the active ingredient on the surface of the support. This is why the catalyst support properties are critical for this process (Ward, 1983, Le Page et al., 1992, Speight, 2004; Zakirova et al., 2023). Consequently, a continuous effort is dedicated to developing enhanced support formulations through appropriate preparation methods, resulting in convenient composition of the surface and textural properties that promote the full utilization of the deposited active phase by allowing sufficient diffusion of the feed molecules. The influence of the properties of the catalyst support on the activity and selectivity of the catalysts were investigated in a review study by (Ward, 1983). It was concluded that the stabilization of sulfides, group VI and VIII oxides in highly dispersed phases, the optimization of the purity of the active phase, tailoring pores of adequate size and structure, thermal stability and low cost are the main inherent properties that the catalyst support should fulfill (Luck, 1991; Marafi,et al., 2019; Rana,et al., 2020).

Advances in residue hydro-processing are achieved with a combination of reactor design improvement and the development of catalysts. The hydro-processing technology is now a well-established technology despite the variation of the effect of these factors depending on the type of hydrotreating (HDT) process. These processes have been widely used in refineries worldwide, for hydrodesulfurization (HDS), hydrodenitrogenation (HDN) and hydrodemetallization (HDM), mostly with fixed bed reactors, moving bed reactors and in some cases, slurry reactors (Luck, 1991). In addition, research and development efforts focused on the enhancement of catalyst properties and porosity have gained increasing attention recently because of the vital role they play in heavy oils upgrading processes. The composition of the catalysts that are utilized in residue hydro-processing technology consists of oxides of Ni, Co, Mo, $andW$ on a matrix or carrier of alumina, silica, silica/alumina (Raynal et al., 2016).

Fixed-bed reactors (trickle bed reactors) are commonly used for the desulfurization process. In these reactors, hydrogen and the feed material enter the reactor from the top and flow downwards, passing through the bed of stationary catalysts. The catalysts for this process are arranged in a series of beds and they are characterized by increased pore sizes and higher capacity for the processing of asphaltene and metals as well (Speight, 2013, Raynal et al., 2016). The first bed is called a guard bed because it serves as protection for other catalysts from poisoning with Nickel and Vanadium (Rana et al., 2007, Speight, 2013). The catalysts are regenerated until they have been excessively contaminated by the metals, then they are replaced. Therefore, for the cost-efficiency of this process and increasing the lifetime of the catalysts, the feedstock needs to undergo preliminary processing to decrease its content of metal. The reaction rate can be enhanced by raising the inlet temperature, which decreases due to the exothermic nature of the reaction. The increase of the reaction rate can also be achieved by using catalysts of smaller size, increasing the surface available for the reaction, but this also increases the pressure drop in the reactor, which can cause physical damage to the internal parts of the reactor (Speight, 2013).

The same active metal components of the catalyst used in the fixed bed reactors are utilized in the ebullated bed process. However, the difference is in the shape of the catalyst as extruded catalysts are chosen for use in the ebullated reactor, while for fixed bed reactors, trilobal, cylindrical, quadrolobe, or quincunx-shaped catalysts are chosen (Raynal et al., 2016). These ebullated beds are expanded beds which are also referred to as particulate fluidized beds, where the catalysts are in an expanded state, allowing the passage of the external feedstock material without plugging. The hydrogen and feedstock are entered from the bottom of the reactor and flow upwards through the bed of expanded catalysts which in random motion. This random motion of the catalysts ensures almost complete back-mixing as well as isothermal operation of the reactor (Rana et al., 2007, Speight, 2013; Yuan et al., 2023). The small size of the extrudate catalysts ($0.8mm$) used in these beds provides higher desulfurization efficiency and the possibility to withdraw and replace catalysts during operation is an advantage of using this process. Oher advantages of this process is its ability to handle heavy feedstocks with high content of impurities and the fixed temperature during operation (Speight, 2013).

Unlike the catalysts described for these beds, the catalysts for slurry beds are unsupported, different in size, mechanical strength and have distinct physical properties (Liu et al., 2019). These catalysts are disposal and flow upwards in the reactor, along with the feed material and H_2, in the form of a slurry. The typical reactor temperature for the hydroprocessing of heavy oil is between 440 and 460°C, while the pressure is maintained between 10 and $15MPa$. As for moving-bed reactors, the catalysts' shape is optimized to limit abrasion and grant the particles increased strength as well. These moving-bed reactors are used for the hydroprocessing of heavy oils that have a high content of metals ($> 300ppm$). The catalysts used in these reactors are called bunker catalysts. They have a high capacity for metals uptake, and they enter the reactor from an opening on the top of the reactor and flow downward (Rana et al., 2007). The flow of the residue and hydrogen can be either co-current or counter-current with the flow of the catalysts, depending on the commercial moving-bed reactor that is chose. The main purpose for the use of these reactors is their high demetallization capacity, while the moving catalysts allow the continuous operation of these reactors. They are also called guard-bed reactors as they are usually employed as preliminary hydrotreating process for the elimination of metals before the subsequent hydro-desulfurization (HDS) and hydro-denitrogenation (HDN) (Speight, 2013).

The mode of operation of each of these hydroprocessing reactors is presented in Fig. 16.

Performance enhancing catalysts were developed for the improvement of the conversion rate. For heavy oil processing, attaining the desired conversion levels requires the optimization of the catalyst properties (selectivity, activity, shape, size and porosity) as well as the adequate selection of the type of reactor, depending on the heavy oil properties. In recent decades, it was noticed that some technologies such as the ebullated bed, moving bed and fixed bed have matured to a certain extent, while technologies such as the slurry bed are still in development (Liu et al., 2019; Felix,et al., 2023).

Finding the perfect match between the feed properties, reactor type, catalyst properties and operating conditions is essential for maximizing the efficiency of the conversion of heavy oil to high-value products. The prediction of the performance of the catalyst and catalytic reactors in the processing of heavy oil feed is very important and the development of computing techniques to achieve this objective is necessary. Additionally, designing advanced and better performant catalyst support is essential because this support, along with adequate porosity of the catalyst can improve as mentioned above the diffusion of large molecules to the active catalytic sites as well as improve the metal retention capacity and increase the surface area. For the prolongation of the catalyst life, the textural properties of the catalyst are optimized to provide higher pore volume that is more suitable for the processing of heavy feed, granted that the surface area is sufficient. Besides, the required acidity must be provided by the chemical composition of the support in order to allow for the hydrocracking, without exceeding the acidity limit in order to avoid the excessive formation of coking products (Castaneda et al., 2014). Hence, due to the importance of the catalyst properties for the success of the conversion of heavy oil, studies on enhancing the stability and life of catalysts, as well as decreasing the catalyst deactivation are necessary.

Some of the main challenges in the catalytic upgrading of heavy oil include catalyst deactivation and waste catalyst production (Raynal et al., 2016). The deactivation of catalysts is a significant problem that causes the loss of catalytic rate. It may occur through various mechanisms, including vapor formation, vapor–solid reactions, solid-state reactions, thermal degradation, poisoning, and fouling (Liu et al., 2019). Table 4 Summarizes the main findings of non-catalytic heavy oil processing technologies.

8.2. Emerging technologies for heavy oil and processing

Due to the scarcity of light crude reservoirs and the inadequacy of present refinery procedures to process heavy and extra-heavy crude oils, a new group of technologies has emerged as a viable solution to this issue. These technologies aim to improve the qualities of those crudes, such as increasing the API gravity, lowering the viscosity, and removing contaminants such as sulfur, nitrogen, and metals, for transportation or refinery feed (Ancheyta, 2023; Rana et al., 2007; Castaneda et al., 2014; AlSamhan et al., 2021; Varfolomeev et al., 2023). Some of the emerging technologies for heavy and extra heavy oil processing are summarized below.

8.2.1. Headwaters heavy oil – Headwaters catalytic (HCAT) process

This process was developed by the Headwaters Technology Innovations Group, and it is a catalytic process for the conversion of heavy oil and residue to lighter synthetic fuels. The colloidal or molecular

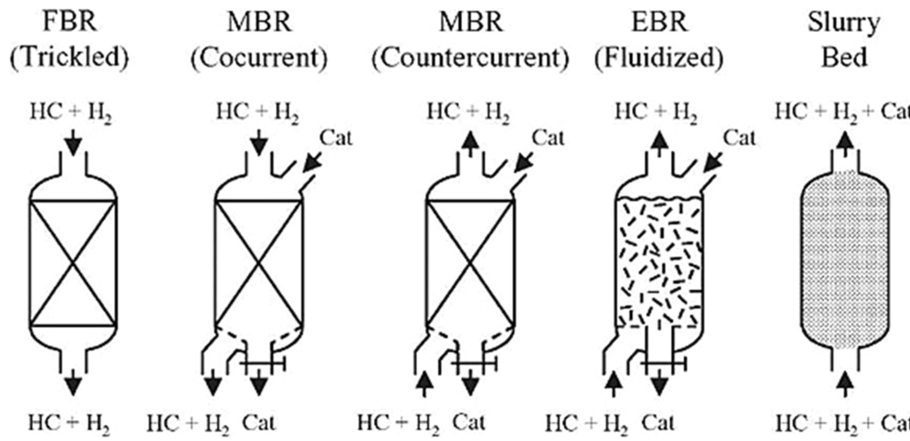

Fig. 16. Types of reactors used in catalytic hydrotreating and their mode of operation.

Table 4
Summarizing the main findings of non-catalytic heavy oil processing technologies.

Process Type	Description
Non-Catalytic Refining	Solvent Deasphalting (SDA): Separates asphaltene using light paraffinic solvents, producing deasphalted oil (DAO). Gasification: Thermal process cracking residue into syngas, carbon black, and ash. Delayed Coking: Converts residue into gas, liquid products, and coke. Fluid/Flexicoking: Converts heavy feedstock into valuable products using a fluidized bed. Visbreaking: Mild thermal cracking to reduce heavy oil viscosity.
Oily Sludge Processing	Combined flash evaporation with solvent deasphalting for oily sludge treatment.
Catalytic Hydroconversion	Fluid Catalytic Cracking (RFCC): Hydrocracking with zeolite catalysts. Hydroprocessing: Hydrocracking using fixed or moving-bed catalysts.
Hydrotreating Processes	Fixed-Bed Reactors: Desulfurization with a series of catalyst beds. Ebullated Bed Process: Desulfurization using extruded catalysts. Slurry Beds: Unsupported catalysts in a slurry for heavy oils with high metal content. Moving-Bed Reactors: Continuous operation for high-metal-content heavy oils.
Challenges/ Considerations	Catalyst Properties: Optimization crucial for efficiency (selectivity, activity, shape, size, porosity). Catalyst Deactivation: Significant challenge through various mechanisms. Process Optimization: Matching feed properties, reactor type, and catalyst conditions for efficiency.

catalysts for this process are chemically generated in-situ and their impressive qualities include high conversion efficiency, feed flexibility, prolonged catalyst activity, uniform quality of the products and the significant reduction of the sedimentation and coke formation, which deactivate the catalysts in conventional processes (Sahu et al., 2015). These catalysts can also be used with supported catalysts to further increase the efficiency of the process. The molecular or colloidal are mixed with a hydrocarbon diluent before being added to the heavy oil feedstock to create a homogenous dispersion of the catalysts within the feedstock, creating a conditioned feedstock. Subsequently, the conditioned feedstock is introduced into a hydrocracking reactor, where the decomposed catalysts promote the reaction between the free hydrocarbon radicals and the hydrogen, forming low molecular weight upgraded hydrocarbons with low sulfur content and avoiding the formation of coke (Lott and Lee, 2009). Ebullated-bed reactors, fixed-bed reactors and moving-bed reactors can all be used in this process for hydrocracking the heavy oil residue. According to some embodiments, a slurry-phase reactor is used for the hydrocracking of the feedstock in the presence of the colloidal or molecular catalysts, while an ebullated-bed or fixed-bed are used, subsequently, for further hydroprocessing of the upgraded feedstock (Lott and Lee, 2009). The typical operating conditions of the reactor include a temperature between 430 and 450°C and a reactor pressure of 13.79*psi* (Castaneda et al., 2014). As shown in Fig. 17, the upgraded feedstock, with a conversion rate between 60 and 98% is then introduced into a hot separator to separate the various synthetic gases and volatile liquids (Lott and Lee, 2009, Castaneda et al., 2014).

8.2.2. Heavy-to-light (HTL) process

This process was invented by Ivanhoe Energy, which is a crude oil upgrading process that is based on utilizing a circulating transport bed for the conversion of heavy oil to synthetic oil that is more transportable, valuable, and lighter. This thermal process consists of the introduction of the feedstock in an upflow reactor, where a particulate heat carrier, which is silica sand, is also introduced at a lower level of the upflow reactor. The particulate heat carrier to feedstock ratio can range from 10:1 to 200:1, with a residence time between 0.5 and 2 seconds and a reactor temperature between 300 and 590°C for the first pyrolysis run. After the pyrolysis of the heavy oil feedstock, the upgraded products of reduced viscosity, low contaminants and high API gravity are separated from the particulate heat carrier afterwards, while the coke formed during pyrolysis is eliminated from the feedstock or is deposited on the silica sand (Fig. 18). The heavier fractions are recycled back into the reactor for a second run of pyrolysis at a temperature between 530 and 700°C. Subsequently, the stream products are separated and collected while the particulate heat carrier is regenerated (Freel and Graham, 2012).

Despite the high yield and high quality products, the small scale of this process is a big disadvantage, as well as the formation of products that can polymerize easily, the low sulfur reduction and the formation of high amounts of coke (Seddig, 2018).

8.2.3. Genoil hydroconversion upgrader (GHU) process

The GHU process is a catalytic hydroprocessing technology based on a fixed-bed reactor and is used for the conversion of heavy oil, residue, and bitumen to marketable fuel (Castaneda et al., 2014). The catalytic reactions for the conversion and hydrotreatment of the feedstock occur in sequences, where the feed material is first introduced into a guard-bed where it undergoes hydrodemetallization to reduce its content of heavy metals, as shown in Fig. 19 (Satchwell et al., 2006). The feedstock is also preheated to a temperature of up to 316°C before being introduced into the main reactor where the hydrocracking, hydro-desulfirization (HDS)

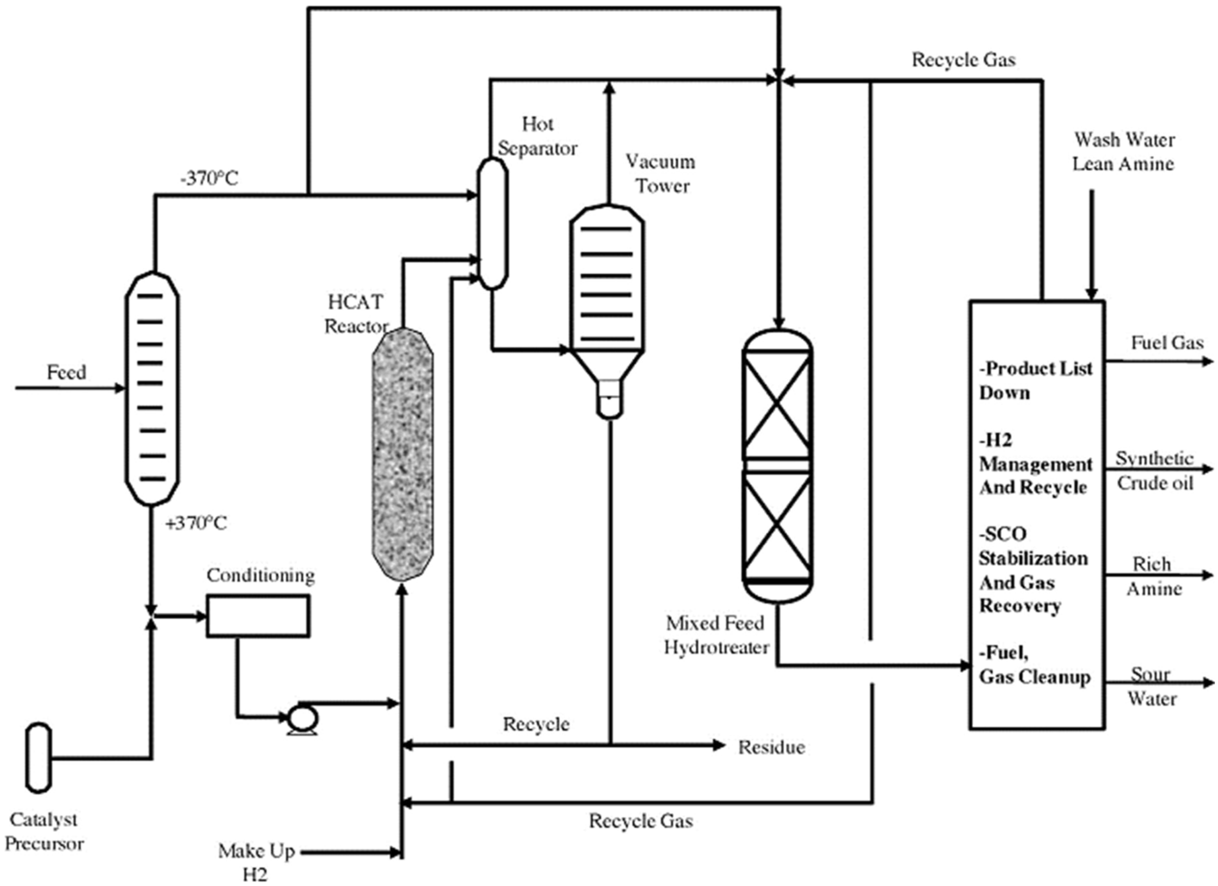

Fig. 17. Schematic illustration of an HCAT process with integrated hydrotreating (Castaneda et al., 2014).

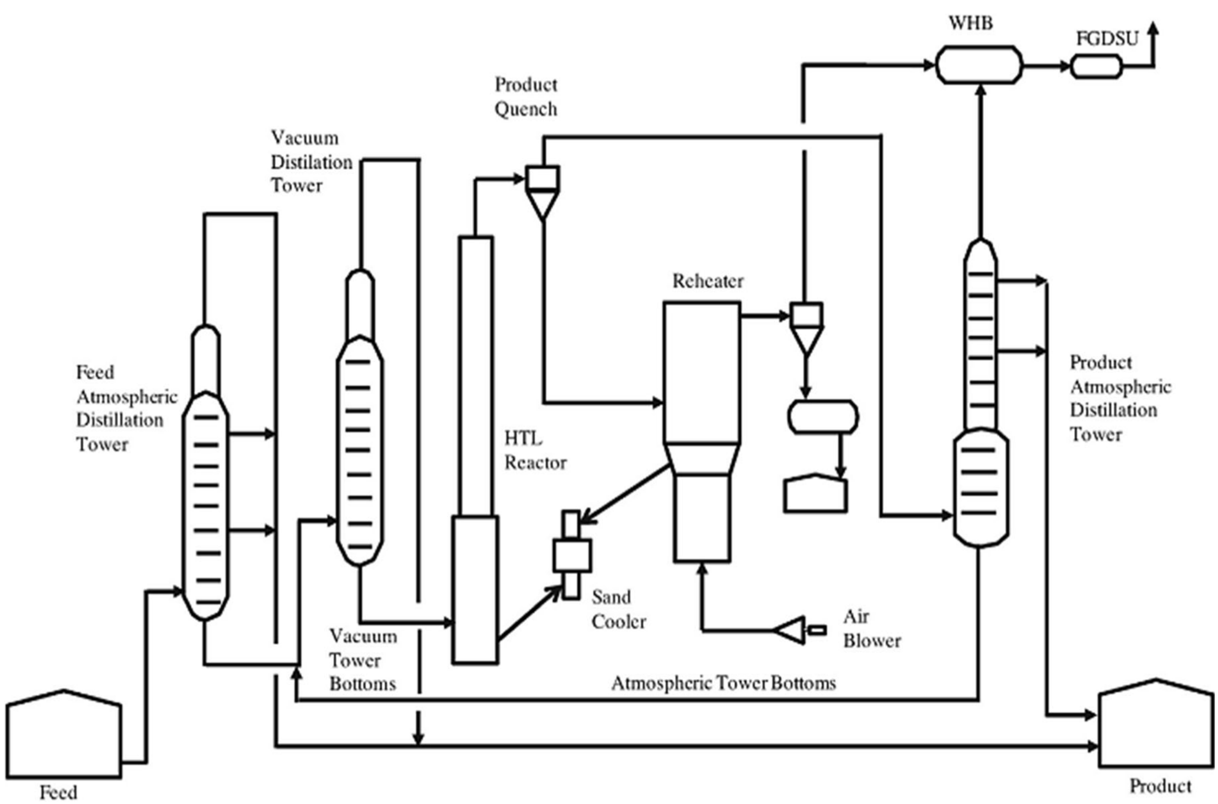

Fig. 18. Schematic illustration of an HTL process in high quality mode (Koshka et al., 2008).

and hydro-denitorgenation (HDN) occur due to the injection of hydrogen and the presence of the catalysts at a temperature of 343 –510 °C (Satchwell et al., 2006, Castaneda et al., 2014). Compared to conventional hydroprocessing technologies, the GHU technology can be operated at mild temperature and pressure conditions (Satchwell et al., 2006). Pilot plant experiments using this process were reported to achieve a conversion rate of 37 –88%, a demetallization rate of 76 –98%, a desulfurization rate of 75 –97%, a denitrogenation rate of 37 –53% and a Conradson carbon reduction of 47 –87%.

8.2.4. Viscositor process

The Viscositor process, which was developed by Ellycrack-Wescorp, a catalytic thermodynamic hydroprocessing technology that is based on the incorporation of a high-velocity chamber, where steam-atomized oil is cracked by collision with fluidized heat carrier (sand). This process does not require the use of an advanced catalyst (Castaneda et al., 2014). In this process, the pre-heated heavy oil is cracked due to the effect of rotating heated sand particulates. First, these fine particles are heated in a regenerator at a temperature of 450 to 600 °C by the combustion of coke, creating a fluidized bed. These heated fluidized particles are transported to the riser from the lower outlet of the regenerator because of the effect of the blowing combustion gases (Ellingsen, 2011). The heavy oil feedstock is pre-heated and steam-atomized before the heat is released from the condensation of the gases, as shown in Fig. 20. In the riser, instant cracking and upgrading of the pre-heated heavy oil feedstock occurs as soon as it is in contact with the blowing air and the heated particles (Ellingsen, 2011, Castaneda et al., 2014). The upgraded heavy oil products and the sand particles are then separated in a cyclone. The oil gas and non-condensable gases are directed towards a dual condensation unit, while the generated coke is used as fuel for the regenerator, where the sand particles are recycled and reheated for a new cycle of heavy oil conversion (Ellingsen, 2011, Castaneda et al., 2014).

The viscositor process is destined for heavy oil upgrading in the oil production field and its advantages include the relatively low temperatures required, the non-requirement of an advanced catalyst and the high metal and sulfur reduction rates which reach up to 90% and 60%, respectively (Ellingsen, 2011, Castaneda et al., 2014).

8.2.5. IMP process

The IMP process, developed by the Mexican Institute of Petroleum, is a cost-efficient catalytic hydroconversion and hydrotreatment technology for upgrading heavy oil with elimination of asphaltene, sulfur and impurities (metallic and non-metallic) as well as impressive conversion rates and reduced sedimentation (Seddig, 2018). The IMP process is carried out over two stages (Fig. 21). In the first stage, the heavy oil feedstock is moderately hydrocracked in a hydrodemetallization (HDM) reactor, which consists of either a fixed-bed or an ebullated-bed of catalysts that have high selectivity for the removal of the metals (Nickel and Vanadium) contained in the feedstock, while the high molecular content of the oil is decomposed by the effect of the heat and produces lighter hydrocarbons by reaction with the injected hydrogen (Juárez et al., 2010). In this stage, the reactor is operated at low-pressure and at a temperature of approximately 538 °C. This hydrotreated feedstock is introduced into a hydrodesulfurization (HDS) reactor for the second stage of the heavy oil upgrading. This HDS reactor also consists of a fixed-bed or an ebullated-bed reactor, operating in similar conditions as the reactor from the first stage, while the catalyst in this reactor is more efficient for the removal of sulfur and nitrogen (Juárez et al., 2010).

The IMP process is intended for use as a first processing unit heavy oil refineries and its moderate operation conditions as well as high conversion rates constitute an attractive return on investment (Castaneda et al., 2014).

8.2.6. NexGen-ultrasound process

The NexGen-Ultrasound Process, developed by Energy Quest, consists of utilizing ultrasound for breaking the heavy hydrocarbons of heavy oil feedstocks. Before the cracking of the heavy hydrocarbons, the water and salt are removed from the heavy feedstock by heating it up to 200 °C followed by a separation of the asphaltene from the heavy oil by membrane separation. The asphaltene and heavy oil undergo a primary partial cracking using a chemical-magnetic induced process that is called the Cracking Process (CP). Afterwards, both the asphaltene and the heavy oil undergo further conversion in a 10-step ultrasound heavy oil upgrader (HOG), which offers the advantage of controlling the ratio of the paraffin–olefin–naphthenic–aromatic (PONA) compounds formed. A subsequent 4-step HOG is utilized to eliminate the sulfur,

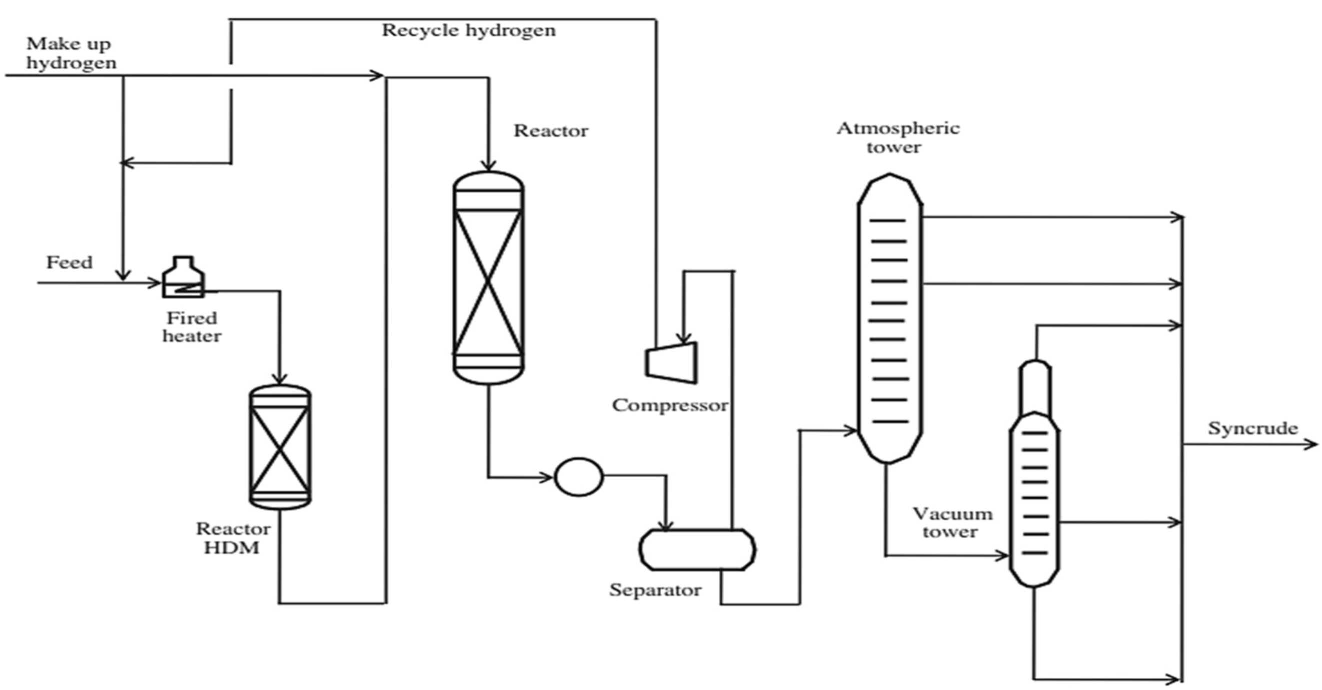

Fig. 19. A schematic illustration of the GHU Process (Liang et al., 2016).

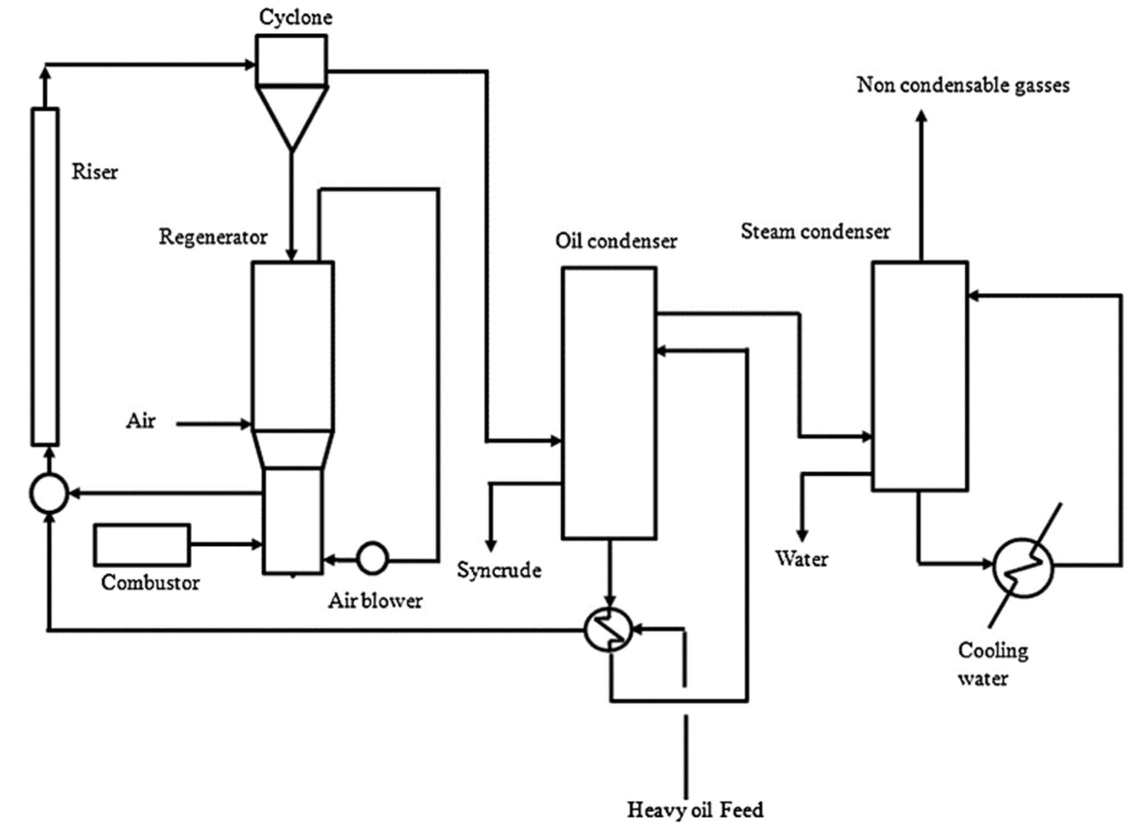

Fig. 20. Schematic illustration of the viscositor process (Alvarez et al., 2014).

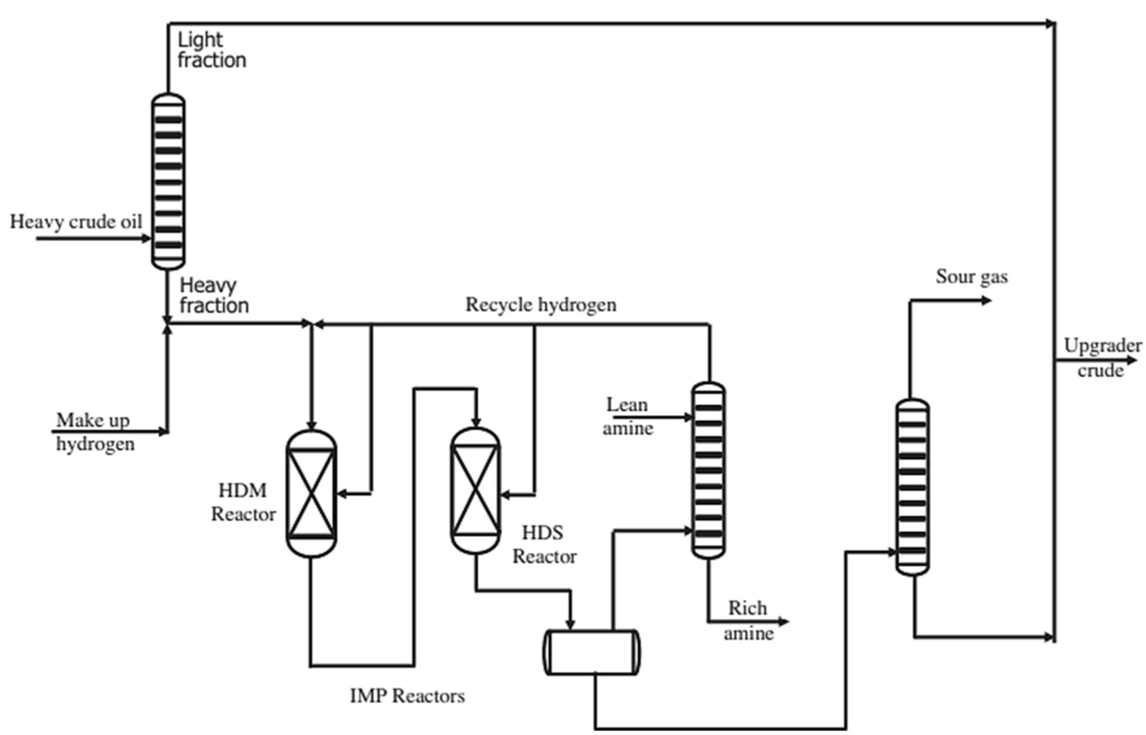

Fig. 21. Schematic illustration of IMP process (Varfolomeev,et al., 2023).

nitrogen, and oxygen content of the upgraded feedstock, creating a light product of high purity and marketability (Castaneda et al., 2014). The final products can then be separated by distillation. Fig. 22 shows a prototype installation of the NexGen-Ultrasound Technology.

8.2.7. *Heavy residue hydro (HRH) conversion*

The HRH process, invented by the Research Institute of Petroleum Industry (RIPI) in Iran, is a catalytic hydrocracking process for upgrading heavy crude oil and extra-heavy crude into marketable products. It consists of several heating steps in which the feed, catalyst and hydrogen are first heated separately, then mixed and heated over the next steps (Castaneda et al., 2014). The heavy oil feedstock is also activated by the addition of modifiers and stabilizers to prepare a catalyst complex that consists of an emulsion of water, pre-activated feedstock, and catalytic compounds. This catalytic complex, along with the feedstock are heated and introduced into a reactor where the heavy hydrocarbons are cracked and upgraded due the injection of hydrogen at a temperature of $430-470^{\circ}C$ and under a pressure of $1-15MPa$ (Khadzhiev et al., 2009). The gas and liquid products of this process, unreacted hydrogen and the catalytic mixture are then separated by distillation and filtration **(**Fig. 23). The untreated hydrogen is treated in amine contractor and recycled to the system, while the catalysts are recovered from the catalytic complex (Khadzhiev et al., 2009, Castaneda et al., 2014).

The conversion rate for this process was reported to exceed 95%, along with a desulfurization yield of 60% (Khadzhiev et al., 2009).

8.2.8. Catalytic crude upgrading (CCU)

The CCU process is a catalytic hydrocracking process that is based on the principles of the fluid catalytic cracking (FCC) technology (Hedrick et al., 2006). It consists of cracking the heavy oil feedstock to reduce its viscosity just enough to allow its transportation via the pipeline. In this process, the main unit is similar to an FCC unit where the primary feedstock of heavy oil, which consist of $20-40\%$ of the total feedstock, is cracked in the presence of a finely powdered catalysts in a fluid-bed reactor at a temperature of $495-550^{\circ}C$ (Hedrick et al., 2014). This process results in the production of cracked crude oil, off gas and coke on the spent catalysts. The cracked crude oil is mixed with a non-cracked feedstock of heavy oil at a ratio of second heavy oil feedstock to cracked heavy oil feedstock between $0.5:1$ and $9:1$, to achieve a mixed feedstock of an API gravity of at least 18, a low viscosity that does not exceed $10,000cSt$ at $38^{\circ}C$ and a pour point lower than $20^{\circ}C$. These properties of the mixed feedstock meet the specification for its transportation via the pipeline. The coke is separated from the catalyst, and it is used as fuel for steam generation and power production for the processing complex, while the catalysts are regenerated for recycling (Hedrick et al., 2014).

This process is considered an attractive option due to its lower capital cost, its self-sufficiency with regards to utilities, the absence of waste by-product and the high yield of coke that is used for power generation (Hedrick et al., 2006).

8.2.9. Sulph-ultrasound process

The Sulph-ultrasound process, also called sonocracking, is an ultrasound-based technology for the desulfurization and hydrogenation of heavy oil, which was developed by SulphCo. Inc (Yen et al., 2002). In this process, a mixture of the heavy oil feedstock, an aqueous fluid and a hydroperoxide oxidizing agent is created. This mixture is an emulsion that can be created with the addition of a surfactant or with surfactants that are naturally present in the heavy oil. Ultrasound is then applied to the mixture for a short contact time that can be as low as an hour, 20 mins or even 10 mins and under ambient temperature and atmospheric pressure. This ultrasonication converts the dibenzothiophene and other sulfur -bearing sulfides present in the heavy oil to their corresponding sulfones, which are characterized by higher polarity. The high polarity of the formed sulfones allows their subsequent separation using a polarity-based separation process (Fig. 24) (Yen et al., 2002, Mei et al., 2003).

The advantages of this process include the near-complete elimination of sulfur with a desulfurization yield of more than 99%, the short contact time, the ambient temperature and atmospheric pressure at which the process operates and its selectivity for the removal of sulfur without affecting non-sulfur-bearing compounds (Yen et al., 2002, Mei et al., 2003**)**.

8.2.10. Eni slurry technology (EST process)

The Eni Slurry Technology, invented by Eni Group, is a catalytic hydrocracking and hydrotreating process that allows the near-complete conversion of heavy crude oil, with a Conradson carbon residue reduction of more than 97%, metals removal rate of 99% or more, a desulfurization rate that exceeds 85% and a denitrogenation rate above 40% (Delbianco et al., 2007, Castaneda et al., 2014). This process is based upon the use of a slurry-bed reactor in which the heavy oil feedstock is converted in the presence of nano-sized particles of molybdenum-based hydrogenation catalysts, under a temperature of $410-420^{\circ}C$ and a pressure of $16MPa$. As shown in Fig. 25, the products of the slurry-bed reactor are introduced into a fractionator where the atmospheric and vacuum distillates, C1-C2 gas and LPG are recovered (Delbianco et al., 2007, Delbianco et al., 2008). On the other hand, the products that settled at the bottom of the fractionator are sent to a solvent deasphalting (SDA) unit, where the deasphalted oil (DAO) is separated from the feed and recovered, while the unconverted residue is added to the new feedstock and will undergo the upgrading conversion process again. The catalysts are characterized by their ability to maintain high activity upon consecutive regeneration and recycling, which encourages the use of a high concentration of the catalysts and hence leading to the high conversion and upgrading rates of this process(Delbianco et al., 2007, Delbianco et al., 2008).

These emerging technologies and others that are in development for heavy and extra heavy oil processing take in consideration the new advancement in information technology, automation and digitalization including electronic monitoring, big data analytics, artificial intelligence, and the internet of things. Radio-Frequency Identification (RFID)

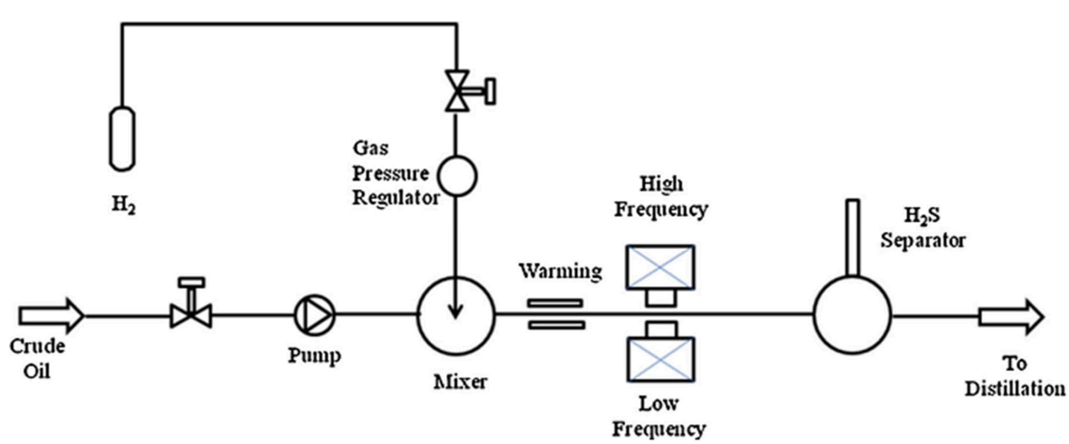

Fig. 22. A schematic illustration of a prototype installation of NexGen technology (Zhao et al., 2021).

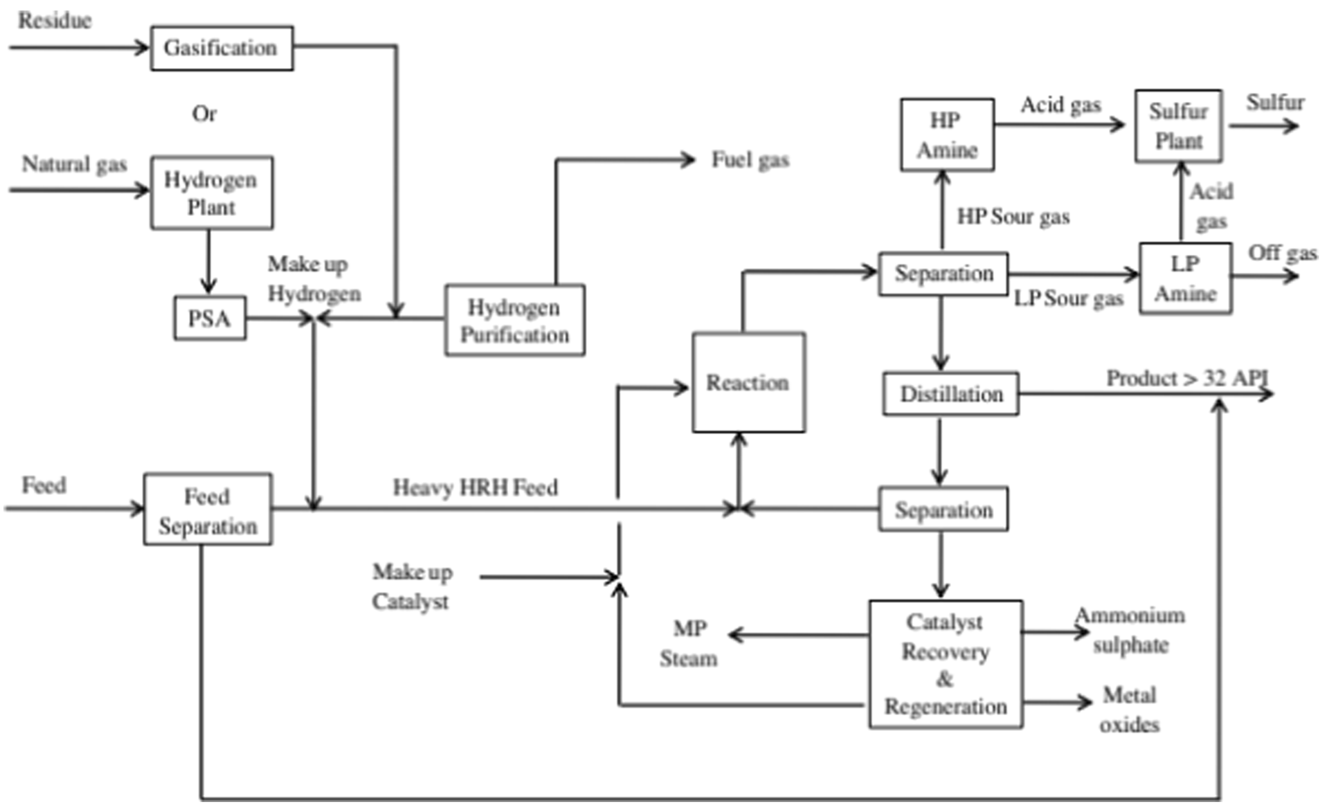

Fig. 23. Schematic illustration of the HRH process (Zarkesh et al., 2008).

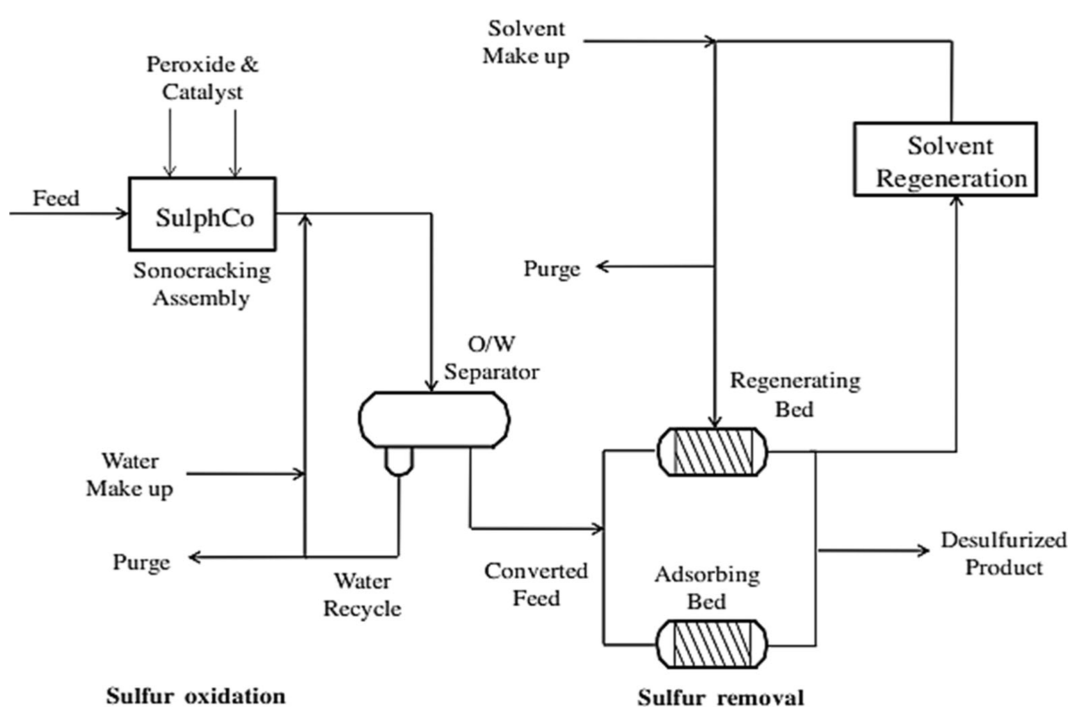

Fig. 24. Process block flow diagram for the Sulph-ultrasound process (Mei et al., 2003).

and Global Positioning System (GPS) devices are examples of Internet of Things (IoT) devices that lower risk, reduce cost, and boost operational efficiency (Mohammadpoor and Torabi, 2020). Table 5 Summarizes the main findings of heavy oil catalytic processing technologies.

9. Petroleum industry digitalization

In the last few years, there has been a shift towards the emerging Industrial Internet of Things (IIoT) and the use of advanced software for analysing data with the overall goal of optimization of process operations and downtime reduction. An IIOT enabled firm is equipped with a

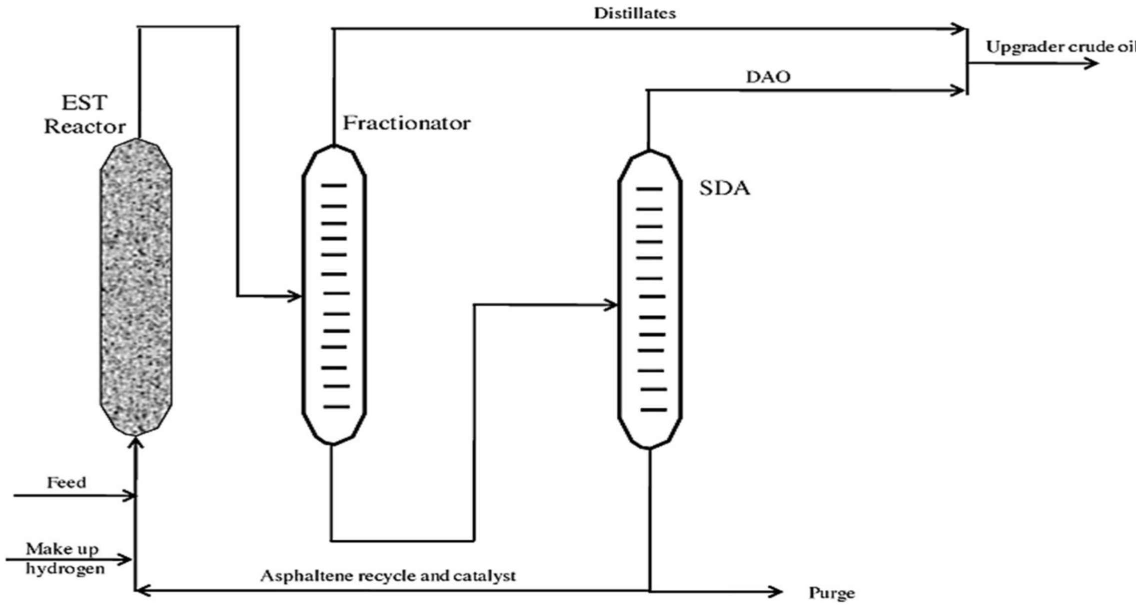

Fig. 25. Schematic illustration of the EST process (Delbianco et al., 2008).

blend of automation systems, sensors, and, most importantly, cloud-based technologies incorporated with the system currently in use by the petrochemical units or refinery (Speight, 2004). These numerical techniques can allow the prediction of the system's output based on the properties of the oil as well as identifying undesirable process patterns, foreseeing potential problems, and hence establishing a warning system so that measures are taken to prevent these problems.

With the aim of improving their production rate and quality, petrochemicals and refinery enterprises rely on digital tools that improve the plants' ability to access the IIoT advantages and allow for the visualisation and simulation of the system. Additionally, the refiners can also leverage the benefits that come with IIoT enabled digital systems in making their decisions through data aggregation from adverse sources (Speight, 2004). Initially, the cost-effective generation of data, which was lacking, could have enabled the use of technologies including analytics and pattern recognition that may guide actions based on the mathematical modelling of processes and the possibilities they provide in predicting the output of the system. Such technology is usually handy in predicting the possibility of leakage of dangerous waste products in refining heavy oil. The qualities of paving asphalt, for example, are determined by its design and content (Shui et al., 1997). Some computational methods, like computational fluid dynamics (CFD) and the discrete element method (DEM), allow for the simulation of the flow regimes, flow behaviour and patterns inside of multiphase reactors and pipelines (Wu et al., 2020, Messa et al., 2021). The incorporation of these tools to simulate the effect of process parameters on the refining of crude oil can be of critical importance to the improvement of these processes, their optimization and identification of problems. Advanced non-invasive techniques such as Gamma-ray densitometry, Gamma-ray computed tomography and radioactive particle tracking are excellent for providing an accurate understanding of the flow regime, flow behaviour, suspension properties, viscosity, pressure drop, phase distribution and holdup of crude oil and its derivatives during various stages of processing (Khane and Al-Dahhan, 2017, Toukan et al., 2017, Qi et al., 2020, Qi et al., 2022, Sabri et al., 2022, Sultan et al., 2022), (Larachi et al., 1997, Schlieper, 2000, Pires et al., 2010). These methods allow the assessment of the system's performance and provide benchmark data for the validation of the CFD and DEM simulations.

Table 5
Summarizing the main findings of heavy oil catalytic processing technologies.

Technology	Key Features
HCAT Process	Catalytic process for heavy oil to lighter fuels. In-situ catalyst generation. High conversion efficiency, reduced sedimentation.
HTL Process	Upgrading via circulating transport bed. Multi-run thermal pyrolysis. Recycles heavier fractions.
GHU Process	Catalytic hydroprocessing. Fixed-bed reactor, mild conditions, high conversion, reduced heavy metal content.
Viscositor Process	Catalytic thermodynamic hydroprocessing. High-velocity chamber for oil cracking. No advanced catalysts, high metal, sulfur reduction.
IMP Process	Two-stage catalytic hydroconversion. Moderate conditions, high conversion rates.
NexGen-Ultrasound	Ultrasound-based heavy oil breaking. Primary cracking, controlled feedstock composition.
HRH Conversion	Catalytic hydrocracking. Multi-step process, gas/liquid separation, catalyst recovery.

10. Cleaner fuels

Fossil fuels are still the primary source of energy globally. Even though there is considerable momentum in the shift towards more green or sustainable energy sources, fossil fuel will still remain the primary source of energy, at least for the foreseeable future (Al-Yatama et al., 2018; Varfolomeev et al., 2023). This is because fossil fuels such as natural gas, propane, oil, and coal are still the most economical and available sources of energy, compared to the alternatives.

However, due to the increasing risks of global warming and climate change, the industry of crude oil is adapting its industrial processes to meet the newer instructions. These instructions mainly address limiting the emission of carbon and other greenhouse gases (Carrillo and Corredor, 2013). Therefore, a major focus is deployed into developing cleaner hydro-conversion technologies for heavy oil processing with lower carbon emissions. The reduction of the energy used in the processing of crude oil is also of interest as some technologies like CCU can be used for the steam and electricity generation in the oil field for use by other processing units.

Increasing the hydrogen content of the oil is not only an effective way for the valorization of the oil but also for the increase of the energy output, as shown in Fig. 1**c**. This means that the increase of the H/C ratio of the oil can lead to reducing the consumption of fossil fuel and thus reducing the emissions that emanate from the burning of fuel.

11. Remarks

The current upsurge in interest in upgrading heavy oils is attributed to the exhaustion of the light crude oil, especially in countries renowned for its production, compelling the researchers to develop innovative technologies for converting heavy petroleum into marketable, high-value products. The primary objective of these innovations is to overcome the challenging properties of heavy oils such as their low API gravity, high content of asphaltene and other high molecular weight hydrocarbons content, high sulfur, and high metals and impurities content. The current processing technologies are being modified in order to accommodate the heavy oil feedstock with reasonable success, while the emerging technologies are either at the initial stage of development or still being tested at various experimental scales. The most notable technologies for upgrading heavy oil are based either on the rejection of carbon or on the addition of hydrogen, with higher efficiency for technologies based on hydrogen addition.

The complex nature of heavy oil requires oil industry to rethink and adapt the conditions of operations, reactor type, new catalyst, and general flexibility in oil processing. Consequently, then economic feasibility and marketability of the products of heavy oil is a challenge because the increase in the cost of oil processing coupled with the low conversion rates of heavy oil, compared to light oil, leads to the production of expensive low-quality products. However, hydrotreatment and some emerging processes have proven to achieve high conversion rates during heavy oil with low sedimentation and acceptable processing costs. These processes can help overcome the sedimentation of undesirable byproducts, which lead to the hindrance of oil transportation and damage to the equipment, thus increasing the cost of production.

Traditional heavy oil upgrading technologies, such as coking and visbreaking, are very energy-intensive and produce significant greenhouse gas emissions. These technologies require high temperatures and pressures to break down the complex and large heavy oil into lighter, more valuable products. In addition to being energy-intensive, traditional heavy oil upgrading technologies produces pollutants, such as sulfur dioxide and nitrogen oxides along with a significant amount of greenhouse gases like CO_2. Hence, as a result of these environmental concerns, there is a growing interest in developing more sustainable heavy oil upgrading technologies. These technologies aim to reduce the energy consumption and greenhouse gas emissions of the upgrading process, as well as to minimize the production of other pollutants.

The matter of fact that the development of sustainable heavy oil upgrading technologies is an ongoing process, and there are a variety of technologies at different stages of development. Some technologies, such as hydrogenation and hydrocracking, are already commercially available and widely used. Other technologies, such as catalytic deasphalting and solvent-based deasphalting, are still in the pilot or demonstration phase. The emerging technologies, such as microwave-assisted deasphalting and ionic liquids-based deasphalting, are still in the early stages of research and development. The rate of development of these technologies is being driven by key factors, including the cost, energy consumption, applicability on a commercial scale, and the need to reduce the environmental impact of heavy oil upgrading.

The key alliance between policy interventions and basic research lies in the integration of government and corporate financial support, carbon pricing mechanisms, technology transfer facilitation, and the deployment of sustainable heavy oil upgrading technologies. Simultaneously, basic research should focus on refinery integration, catalyst development, reactor design, data simulation, reaction mechanisms, kinetics, energy integration schemes, electrification for healing such as microwave and induced heating, and ultimately, sustainable development assessment.

Accordingly, the selection of processing technologies for heavy oil is critical and important, as there is no general rule that can provide all the refineries a solution to the prevailing challenges, they might be predisposed to during heavy refining oil. Factors such as oil prices, trends in the market, prevailing needs at local levels, chemical and physical properties of available residua and heavy oil and the configurations of the refinery need to be considered in the definition of an upgrading scheme that is specific to a particular plant. In short, every refinery should define an individual scheme for upgrading and processing heavy oil based on the oil properties and available technologies, as well as integrating the refineries with petrochemical complexes in order to improve the cost-efficiency of heavy oil processing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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