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HIGH-VISCOSITY CRUDE OIL. A REVIEW

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Abstract. The current problem of the production and processing of heavy high-viscosity oils in Ukraine and the world has been considered. It has been established that the main reserves of heavy high-viscosity crude oils in the world are located in South and North America, in the Middle East, as well as in Ukraine in the eastern regions. An analysis of various classifications of heavy high-viscosity oils, which are used both in Ukraine and in the world, was carried out. The main extraction methods of heavy high-viscosity oils were considered, in particular, quarry, mine, and well extraction methods. An overview of the technological processes of heavy high-viscosity oil processing was carried out.

Keywords: high-viscosity oil, heavy oil, heavy oil recovery, viscosity, emulsion.

1. Introduction

Economic development and impressive population growth in recent decades have led to increased demand for fossil fuels. This has led to a decline in so-called "conventional" oil reserves, including light and medium-viscosity oil, which are dwindling and insufficient to meet ever-increasing fuel and energy needs. Unconventional oil reserves, which include heavy high-viscosity oil (HHO), extra-heavy oil, oil shale, oil sands, tar sands, and bitumen, are an alternative to fossil fuels. It is expected that in the future heavy and extra-heavy oils will become excellent alternatives to conventional oils, but taking into account their chemical composition and physicochemical properties, it is necessary to solve several problems related to their extraction, further transportation to the oil refinery and further ways of their rational processing.[1-2]

Heavy high-viscosity crude oil is a mixture of liquid hydrocarbons, which is characterized by a density of 920–1000 kg/m^3 and a viscosity of 10–100 mPa·s. Heavy oil deposits lie at all depths ranging from 300 m to more than 1500 m^3. Heavy oils contain a high content of aromatic hydrocarbons, tar-asphaltene substances, and a high concentration of metals and sulfur compounds; they have high values of density and viscosity and increase coke ability.[3-5] As a result, this causes an increase in the production cost, as well as an increase in the transportation cost through existing oil pipelines and complicated oil refining according to classical schemes.[3]

The peculiarity of HHO is the presence of a large group of microelements in it, first of all, vanadium, nickel, iron, and sulfur, having a special place. There is also increased radioactivity and low gas content (mostly less than 30 m^3/t). Gas dissolved in HHO is "dry", the methane content is about 90 % or more, and the presence of "fatty gas" is typical for conventional oils.[3,4]

The volume of heavy oil reserves in the world (Fig. 1) was found to be 434 billion barrels according to the evaluation of the U.S. Geological Survey.[6,7]

As can be seen from Fig. 1, the vast majority of heavy high-viscosity oils are located in North and South America, as well as in the Middle East.

Canada, Venezuela, and South America have ≈90 % of all known heavy oil reserves.[7-9] The growing importance of HHO, in the perspective of global energy demand, was repeatedly mentioned in a series of research.[8-11]

As can be seen from Fig. 2, Canada, Venezuela, and Brazil were the leaders in global production of HHO in 2017, producing more than 5.75 million barrels per day together.[12]

HHO reserves (%) located in Eurasian countries are shown in Fig. 3.

As can be seen from Fig. 3, the vast majority of heavy oils are located in the russian federation, Kazakhstan and Azerbaijan, totaling 7.32 billion tons.

Contrary to popular opinion, Ukraine is a country with a sufficiently powerful subsoil hydrocarbon resources potential,[3] which is formed from both "conventional" and "unconventional" hydrocarbon sources. In Ukraine, mostly high-viscosity oil is produced, the reserves of which are successfully sold and processed in the USA, Canada, and other countries of the world. This type of oil is extremely relevant for Ukraine because it is a complex raw material for a number of the national economy sectors though today it is not given enough attention.[3,13-16] For example, components of motor fuels and distilled bitumen which are obtained from HHO and properly modified, may be used in various industries, *e.g.* for road construction.[17-24]

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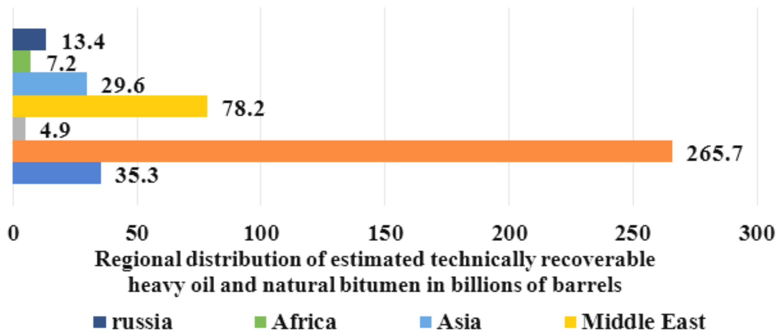

Fig. 1. Evaluation of heavy oil reserves in the world[6,7]

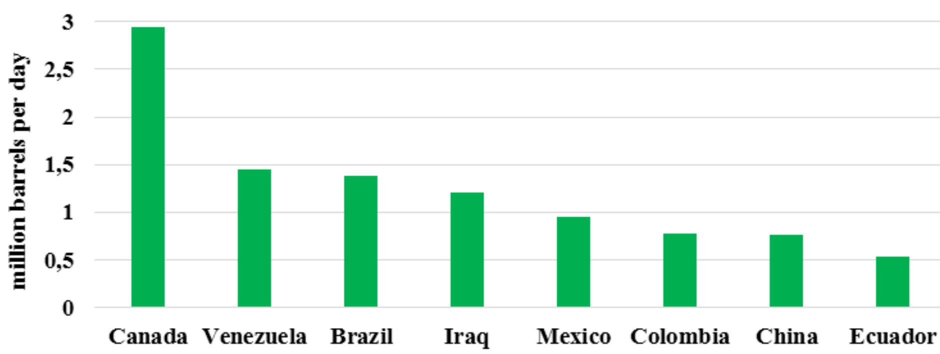

Fig. 2. World's largest heavy oil producers

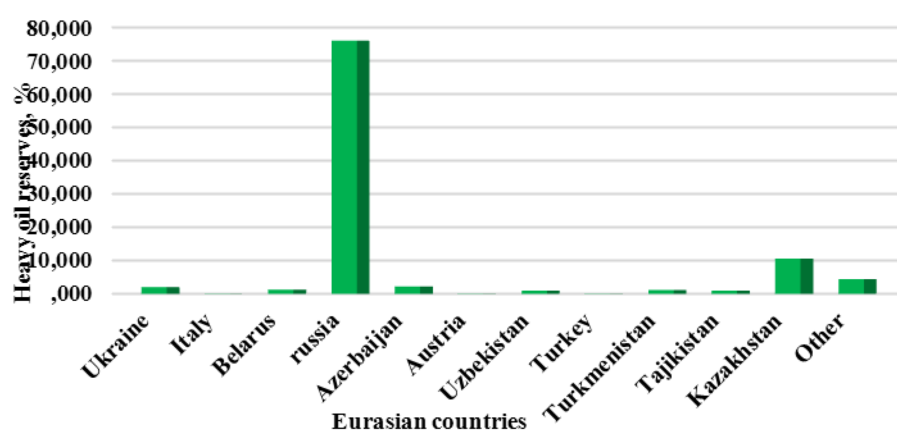

Fig. 3. Heavy oil reserves in Eurasian countries

There are all the geological prerequisites for the accumulation of significant deposits of heavy types of oil and bitumen in Ukraine. The most important and promising deposits are in the extreme northwest of the Dnipro-Donetsk depression, where deposits of heavy oil, maltene, and asphaltene have been known for a long time.[3,25] Within the large promising Volyn-Podilsky oil and gas region, one should expect the discovery of large oil-bitumen deposits, as there is every reason for this, by analogy with the geologically close Western Canada. At least 2 billion tons of heavy oil and bitumen are concentrated in Ukraine, this is only according to the most modest estimates. This figure may increase significantly, as drilling and a detailed study of the forecast oil-bitumen layers of Ukraine are underway.[3,25]

At the same time, the share of hard-to-extract reserves in the structure of hydrocarbon reserves is constantly increasing, the development of which in modern economic conditions is associated with significant investments. Therefore, the development of such fields with hard-to-extract oil reserves is slow and, as we can see from experience, the final oil yield of the productive layers of these fields does not exceed 30 % of their initial balance reserves.[27] In Ukraine, these are, first of all, oil reserves in low-permeability reservoirs, residual hydrocarbon reserves formed at a late stage of field development, high water-cut deposits, heavy high-viscosity oil (Fig. 4), as well as bitumen.[26, 27]

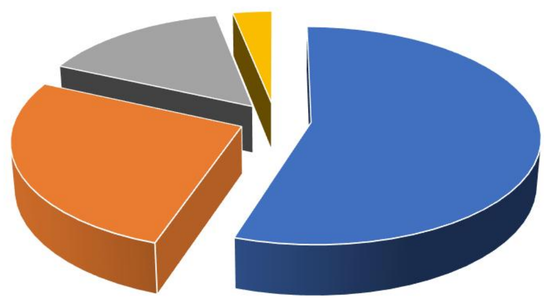

Fig. 4. Structure of hard-to-extract oil reserves in Ukraine[26]

2. Classification of Heavy High-Viscosity Oils

The classification of HHO will be considered in more detail since in the future it will affect the methods of its processing. Heavy oil, extra heavy oil, oil sands, tar sands, oil shale, and bitumen are unconventional oil resources.[7] The above terms, which may confuse due to similar key characteristics, are presented by these resources.[7] The general classification of oil is related to its fluidity and, therefore, indicates the specific technical characteristics of its production, transportation, and processing. Oil companies and government agencies usually adopt oil definition criteria that take into account financial aspects and the degree of technological improvement. Because they represent particular and temporal variations, these criteria are of limited use. In oil refineries and oilfields, the acceptance criteria are usually related to oil properties such as density and viscosity.[7]

The most common definition of heavy oil is based on its density according to the API gravity scale, proposed by the American Petroleum Institute (API), which uses this scale in degrees API (an index based on the relative density of oil) as a criterion for classifying oil. The range of API grades chosen to define and classify oils is not standardized. The API oil classification is shown in Table 1 and is often used to differentiate the various types of crude oil, each of which has its specific processing problems.[27]

Table 2 summarizes some of the main aspects related to the use of different types of crude oil in refineries.[27]

Table 2 shows that the use of such oil is not always easy and requires certain preparation before its delivery to the refinery.

Stebelska[28] proposed a classification of industrial oils according to which low-viscosity oils include oils with a viscosity of less than 10 mPa·s; viscous oils – 10–100 mPa·s, and high-viscosity oils – more than 100 mPa·s (this applies to issues of oil transportation or processing). When solving certain project tasks for the development of oil deposits, low-viscosity oils include oils with a viscosity of 1–5 mPa·s, oils with an increased viscosity of 5–30 mPa·s, and high-viscosity oils – more than 30 mPa·s. Thus, this discrepancy in determining the values of oil viscosity classification limits causes a lack of clarity in the terms "viscous" oil and "high-viscosity" oil.[28]

The resolution of the Cabinet of Ministers of Ukraine dated November 7, 2013 No. 838 26 outlines the criteria by which the category of reserves is defined as hard-to-extract reserves.

Table 1. Oil classification by the API[27]

Heavy sour crude	API < 26 >1 wt-% sulphur
Extra-heavy crude or bitumen	API < 10 High metals content Extra heavy oil viscosity 100-10000 cP at 60F, Bitumen viscosity >10000 cP at 60F
High acid crude	TAN > 0.5 mg KOH/g Typically heavy, API < 26
Oil shale	API 19 – 34 0.5–1.0 wt-% sulfur 1.2–2.0 wt-% nitrogen

Table 2. Oil classification in refineries[27]

Heavy sour crude	• Dewatering & desalting issues • Yield Distribution (higher vacuum residue yield) • Catalyst contamination & deactivation • Corrosion issues (sometimes reduced by high sulfur contents) • Upgrading quality and product properties • Fouling and other processing issues
Extra heavy / Bitumen crude	• Dewatering & desalting issues • Sampling issues due to uneven distribution of water • Yield distribution (vacuum residue yield) • Product properties • Various catalyst issues in upgrading • Fouling and other processing issues
High acid crude	• Dewatering & desalting issues • Increased corrosion in refinery units • Effect of acidity on product properties • Various catalyst issues in upgrading due to high metal content • Fouling and other processing issues

Table 3. Industrial classification of oils[28]

Type of oil	Content, %			Features of deposit development
	resins and asphaltenes	paraffins	sulfur	
conventional	up to 10	up to 10	up to 0.5	this type of oil can be developed in natural depletion regimes without the introduction of any secondary methods and agents acting on the near-well zone of the formation (NZF); complications occur during the operation of wells that are not related to the physicochemical properties of the oil.
abnormally paraffinic	less than 5	more than 10	up to 0.5	such oils can be developed in natural depletion regimes; due to the formation of paraffin plugs in the tubing and loops, clogging of the NZF due to cooling (with the gas lift method of operation), complications occur during operation.
abnormally resinous	from 11 or more	less than 5	more than 0.5	development by traditional methods is inefficient or impossible for this type of oil; mandatory implementation of secondary development methods using horizontal wells and reservoir agents; the exploitation of these oils is complicated with the introduction of solvents into the well, therefore there is a frequent failure of the good equipment associated with the manifestation of the rheological properties of HHO and NB.

These are areas from which extraction of hydrocarbon reserves is complicated by the presence of at least one of the following criteria:

– oil deposits belong to the category of high-viscosity (with dynamic viscosity in formation conditions over 30 mPa·s);

– the reservoirs of the relevant subsoil areas, in which reserves of hydrocarbon raw materials are located, have low permeability (less than 0.05 μm^2 for oil and less than 0.02 μm^2 for natural gas);

– oil reserves are located in the oil borders and sub-gas zones of oil and gas condensate fields with an oil deposit height of fewer than 30 meters and a width of no more than 200 meters;

– the degree of extraction of initial oil reserves is more than 80 %, of natural gas – more than 85 %;

– the average water-cut of oil deposit products is more than 80 %, provided that more than 60 % of the initial production reserves are extracted;

– in gas deposits with an active water pressure regime where more than 40 % of the initial balance gas reserves have been extracted;

– more than 40 % of the initial balance reserves of gas were extracted in gas-condensate deposits with an initial condensate content in formation gas of more than 200 g/m^3;

– gas condensate deposits with initial balance gas reserves are less than 0.5 billion m^3;

– deposits located in marine water areas.

In many industrialized countries of the world, heavy oil is considered the main one for the development of oil production in the coming years. Since more and more heavy oil will be produced in the future, a reliable technology for influencing the rheological properties of crude oil becomes relevant.

3. Production of Heavy High-Viscosity Oil in Ukraine and the World

In Ukraine, geological prospecting works for the search of oil and gas deposits and extraction of hydrocarbon raw materials are carried out in three regions, namely: Eastern, Western and Southern.[26]

Taking into account the fairly large forecast resources of heavy oil and natural bitumen in Ukraine, as well as the positive, albeit limited, the domestic experience of their development, this direction of developing HHO production should be considered a priority. It is necessary to increase the intensity of obtaining synthetic hydrocarbons from the discovered deposits of these naphthides in the developed oil and gas-condensate fields (Yablunivske, Bugrivativske, Skorobagatkivske, *etc.*), also to introduce the development of HHO and bitumen deposits, and most importantly, to start the search and exploration of heavy oil deposits and natural bitumen within the above-mentioned zones with the prospective discovery of their significant reserves at shallow depths.[16]

One such deposit of high-viscosity oil in Ukraine is the Yablunivske field, it is located in the Poltava region, 17 km from Lokhvytsia.[3]

At present, the explored oil reserves of the Moscow and Bashkir deposits of the Yablunivske field amount to about 50 million tons, where more than 90 % of all explored oil reserves of the field are concentrated. The degree of geological study of these deposits remains low, even despite the long-term development of the Bashkir and Moscow oil deposits.[3]

A structural feature of most productive layers of oil and gas fields in Ukraine is a significant distribution of low-permeability reservoirs with increased content of the clay component, which contains significant oil reserves.[26] Low-permeability reservoirs are characterized by complex man-made processes during development due to changes in filtration-capacitive properties, both in terms of area and cross-section of the productive layer. The development of oil fields in Ukraine with low-permeability reservoirs requires the use of modern technologies, including the use of horizontal wells.[26]

The Ukrainian oil refining industry has not yet processed heavy oil. Production of such oils is no more than 1–2 % of total oil production in Ukraine. In the conditions of an acute shortage of domestic oil products, the search and study of heavy oils are extremely important and relevant.[15]

Heavy oil reserves significantly exceed light and low-viscosity reserves and, according to experts, range from 650 billion to 1 trillion tons. This is almost five times more than the reserves of low- and medium-viscosity oils, which are only 162.3 billion tons.[15]

HHO creates many problems during its extraction. During extraction, problems arise due to the inter-repair period of wells and equipment related to subsoil development. The main reason for equipment failure is the presence of paraffins and resinous substances in the oil, which to a greater extent turn the system from an ideal solution into an emulsion. The mentioned substances accumulate on pump parts and transport pipes, which entails more frequent repairs and, as a result, downtime.

At present, there are three methods of extracting heavy oil and natural bitumen: quarry (open pit), mine, and well drilling.[29]

The quarry method is common in Canada. 20 % of Canada's proven bitumen reserves lie in sand reservoirs at a depth of up to 50 m, so this method of extraction is the most optimal. Companies such as OPTI Canada, Suncor, Shell Canada, *etc*. are engaged in oil sand development in Canada.[29]

Mining oil production consists in transferring the production horizon from the surface to the formation or nearby horizons, which in turn allows reducing the back pressure on the formation from the side of the fluid column in production wells to almost zero and fully using formation energy for oil extraction.[29]

The third is the well drilling method of heavy oil extraction. Conventionally, 3 groups can be distinguished in the well drilling method of HHO and NB extraction: “cold”, thermal and combined.[29] Among them, the CHOPS and VAPEX processes, which are widely used in the world, can be singled out.

The CHOPS method (cold HHO extraction with sand) is the primary oil extraction method. It is widely used for oil extraction in Canada (up to 15% of total production). Also, this method has found application in the fields of China and Venezuela.[29] CHOPS envisages the complex production of HHO together with sand due to the destruction of a weakly cemented reservoir and the creation of suitable conditions in the reservoir for the flow of an oil and sand mixture.

Another “cold” method of HHO extraction is the VAPEX process (injection of solvent into the reservoir in gravity drainage mode). This method consists in using two horizontal wells. After pumping a hydrocarbon solvent into the upper well, a solvent chamber is formed. The bitumen is liquefied due to the solvent diffusion into it and flows along the boundaries of the chamber into the well, from where it is extracted under the action of gravity.[29]

4. Technologies for the Heavy High-Viscosity Oils Processing

The processing of HHO is a serious problem due to its physicochemical properties, such as high viscosity, density, low hydrogen content, the presence of high molecular compounds (resins and asphaltenes), a large number of heteroatomic compounds (nitrogen, sulfur, and oxygen), as well as a high content metal, especially nickel and vanadium.[30]

Considering the low quality of heavy crude oil and its transportation difficulty, it is necessary to develop technologies that can improve its physicochemical properties. Conventional methods of heavy oil enrichment can be classified into chemical, thermal, and mechanical ones.[31]

High viscosity and asphaltene content in HHO can affect the process of its transportation and processing. Previous studies have shown that the crude oil viscosity depends on the concentration and chemical structure of asphaltenes, which are the most polar and heaviest component of HHO.[32] Mansouri *et al.*[32] developed a new method of combining ultrasonic waves of different frequencies and magnetic nanoparticles to reduce the asphaltene content and kinematic viscosity of HHO. The results showed that ultrasonic irradiation, with an optimal time of 10 min and a constant temperature of 293 K with a frequency of 25 kHz and a power of 840 W, reduces the asphaltene content and kinematic viscosity of HHO.[32]

Ilyin *et al.*[33] propose using hexamethyldisiloxane for HHO deasphalting, which in turn allows asphalt-resinous substances to be precipitated several times more compared to aliphatic hydrocarbons. It was established that not only heptane-insoluble tarry asphaltene substances in HHO, but also other polyaromatic compounds and paraffins are precipitated using hexamethyldisiloxane.[33]

HHO contains a significant amount of sulfur in the form of various sulfur-containing compounds, such as sulfides, thiols, thiophenes, benzothiophenes, dibenzothiophenes, *etc.*[34]

Ghahremani *et al.*[35] proposed the use of oxidative desulphurization in the presence of ultrasound to reduce the sulfur content in HHO. Al-Bidry *et al.*[36] suggest using natural clays such as bentonite (Fe and H-bentonite) for the same purpose.

One of the most important processes of HHO processing is hydrocracking, in which HHO and its heavy fractions are transformed into light products with improved physicochemical properties. Ghahremani *et al.*[36] propose to carry out the HHO hydrocracking process on a homogeneous nanocatalyst. The novelty of this method consists in obtaining exfoliated MoS_2 nanoparticles and their subsequent use as a new homogeneous nanocatalyst in the hydrocracking process, which in turn improves the HHO processing compared to other catalysts.[36]

Lam-Maldonado *et al.*[37] propose to use NiFe nanocatalysts with different molar ratios (1:0.33, 1:1, and 1:3), which were synthesized by a modified inverse microemulsion method, with the aim of their further application for HHO *in situ* hydroprocessing and improving the physicochemical properties of raw materials.

Rana *et al.*[38] present the catalyst effect, consisting of aluminum oxide and ultra-stable zeolite Y (US-Y), on the hydrogenation processes in HHO processing. The combination of ultra-stable zeolite and aluminum oxide can create the bimodal type of pores in the catalyst which in turn contributes to a better combination of hydrodesulfurization, hydrodemetallization, and the selective cracking of asphaltenes on the acid catalysts.

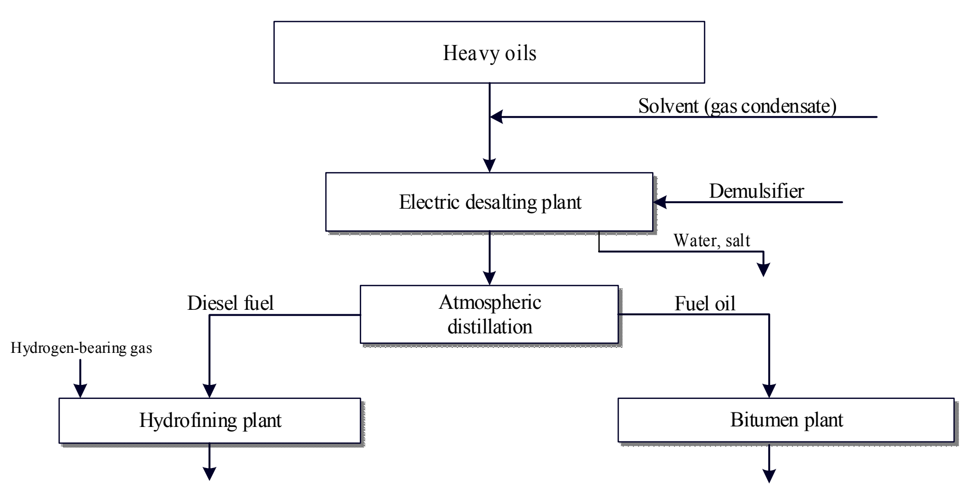

Fig. 5. Flow chart of heavy oils processing

Previously[15], the authors developed a scheme for the processing of heavy high-sulfur oils from the Yablunivske field (Ukraine) (Fig. 5).

Based on the physicochemical properties of the studied oils, the following technological solutions for further processing of heavy high-sulfur oils are proposed (Fig. 5):

– before the desalting process, it is necessary to add a solvent (gas condensate) to reduce oil viscosity and facilitate its further processing;

– the primary oil processing must be carried out at an atmospheric distillation unit. Since there are no gases and gasoline fractions, and the yield of diesel fractions is low, only diesel fraction and fuel oil with a high pour point will be obtained as a result. Since fuel oil contains a significant amount of sulfur compounds, bitumen obtained from such oil will have high adhesive properties;

– the diesel fuel fraction can serve as a raw material for a pyrolysis plant to obtain ethylene and propylene or can be sent to a hydrofining plant for commercial diesel fuel production;

– fuel oil is processed at a bitumen production plant to obtain commercial bitumen.

5. Conclusions

It has been shown that the world's heavy oil reserves are concentrated in North and South America, as well as in the Middle East. Heavy high-viscosity oil reserves significantly exceed light and low-viscosity oils and, according to experts, range from 650 billion to 1 trillion tons. HHO reserves in Ukraine are located in the Western, Southern, and Eastern regions and make up ~2 % of the world reserves.

The classification of HHO by API and the industrial classification of oils, which depend on the physicochemical properties of HHO and the group hydrocarbon composition, were considered, respectively. The physicochemical properties of HHO serve as initial information for the classification of these oils to select further energy-efficient and economically feasible technology for their processing.

The most common methods of HHO extraction in the world are the quarrying method, which has become widespread in Canada, and the well drilling method, which is most often used in China and Venezuela. Among them, the CHOPS and VAPEX processes, which are widely used in the world, can be singled out.

Considering the low quality of heavy crude oil and the difficulty of its transportation, it is necessary to develop technologies that can improve its physicochemical properties. Conventional methods of heavy oil enrichment can be classified into chemical, thermal and mechanical.

Modern technologies for heavy high-viscosity oil processing should include the processes of electrical desalting, hydrodemetallization, and hydropurification to technologically simplify the processing of these oils and obtain a variety of marketable petroleum products for various industries.

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ВИСОКОВ'ЯЗКА НАФТА: ОГЛЯД

Анотація. *Розглянуто актуальну проблему видобутку та переробки важких високов'язких нафт в Україні та світі. Встановлено, що основні запаси важких високов'язких нафт у світі розміщені в Південній і Північній Америці, на Близькому Сході, а в Україні – у східних регіонах. Проаналізовано різноманітні класифікації важких високов'язких нафт, які використовують як в Україні, так і у світі. Розглянуто основні способи видобування важких високов'язких нафт, зокрема кар'єрний, шахтний і свердловинний. Здійснено огляд технологічних процесів переробки важких високов'язких нафт.*

Ключові слова: *високов'язка нафта, важка нафта, видобуток важкої нафти, в'язкість, емульсія.*