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PROSPECTS FOR DEVELOPING THE HYDROCARBON POTENTIAL OF DEPOSITS OF HEAVY HIGH-VISCOSITY OIL, PETROLEUM BITUMEN, RESIDUAL OIL AND FALLING CONDENSATE IN THE SUBSOILS OF UKRAINE

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Abstract. The hydrocarbon potential of heavy high-viscosity oil and natural bitumens (malthas, asphalts, asphaltites) remains practically unexplored and uncertain. At the same time, oil and gas promising areas make up more than 80 % of the territory of Ukraine. Also, an important source of hydrocarbons is non-extractable reserves of residual oil and retrograde gas condensate. Based on this, the purpose of the work was to substantiate the technologies of their development. The objects of the research are the geological conditions of occurrence of heavy high-viscosity oils and petroleum bitumens in Ukraine and promising technologies for their development. On the basis of an in-depth analysis of the features of the formation, occurrence and distribution of deposits of heavy high-viscosity oil and petroleum bitumen, as well as an analysis of the existing methods of their extraction, the work solved the problem of choosing the most effective development technologies for the deposits of Ukraine. Since, according to the results of the analysis, deposits of heavy high-viscosity oil and petroleum bitumen were discovered in Ukraine in the intervals of occurrence of 800–1500 m and 200–500 m (shallow-lying deposits in the composition of sandy sediments), it was proposed for these intervals that the most effective is, respectively, the technology of cyclic steam stimulation in combination with catalytic aquathermolysis. Currently, deposits of high-viscosity oils and natural bitumen are not developed in Ukraine, and, moreover, level of geological study of their resources is extremely low. Therefore, pilot projects of their development are proposed to be implemented in already developed oil fields. The choice of these technologies is justified as follows:

1) the technology of cyclic steam stimulation in combination with catalytic aquathermolysis is expedient to implement on already developed deposits where production is carried out, though the extraction rate of heavy oil is low (with minimal investment and maximum profitability);

2) in view of the accumulated experience in the development of bituminous sand deposits (Alberta, Canada) and having in Ukraine a number of promising deposits similar in depth and type of bedding, it is possible to implement steam gravity drainage technology or its modifications.

Keywords: heavy high-viscosity oil, petroleum bitumen, production technologies, cyclic steam stimulation, well hydraulic production, catalytic aquathermolysis.

1. Introduction

The consumption of natural hydrocarbons (HC) in the world is steadily increasing and, unfortunately, there is no reason to wait for this trend to break at least until the end of the current century. The related energy problems concern Ukraine in the first place. This leads to an increase in the value of non-traditional and alternative HC sources. These are primarily heavy highly viscous oil (HHVO) and natural bitumen (NB) (maltas, asphalts, asphaltites).

Regularities of distribution of oil, gas and natural bitumen deposits on the territory of the Dnipro-Donetsk depression were studied by Ukrainian scientists I.V. Vysochanskyi, V.K. Havrysh, I.V. Greenberg, G.N. Dolenko, V.M. Zavyalov, V.O. Krayushkin, M.R. Ladyzhenskyi, V.F. Linetskyi, B.Y. Majevsky, R.M. Novosiletskyi, V.B. Porfiriev, S.I. Subbotin and others. Most of them considered the placement of deposits in the context of their genesis.

The hydrocarbon potential of these naphthides remains practically unexplored and undefined. At the same time, oil and gas promising areas make up more than 80% of the total territory of our country [1]. In addition, reserves of residual oil and retrograde gas condensate are an important source of hydrocarbons. At the moment, in the absence of effective technologies, they are unextractable. Based on this, the study of patterns of formation and occurrence of deposits of this type and technologies of their development is relevant. This was the purpose of this work.

1.1 Paragenetic relationships of HHVO and their location in the system of natural naphthides

At the same time, clarifying the position of HHVO in the general system of naphthides is of key importance. The wide use of the phrase «heavy (heavy and highly viscous) oils and bitumens» indicates that most researchers tend to attribute HHVO not to NB, but to oils. But from the point of view of physical and chemical properties, not to mention rheological properties and technological aspects, they are closer to malts than to normal (light and medium low-viscosity) oils [2, 3, 4]. HHVO, malths, asphalts in a number of deposits are connected by gradual transitions.

The paragenesis of HHVO, malths, asphalts with oil, gas condensate and gas deposits accumulations is observed in a number of deposits of the Dnipro-Donetsk, Carpathian and Azov-Black Sea oil and gas-bearing regions of Ukraine. For example, at the Bugruvate multi-layer field (northern subduction zone of the Dnipro-Donetsk depression (DDD)), the productive sandy layers of the Visey sediments contain deposits of both conventional oil and HHVO. At the Yablunovka field (the central part of the DDD), along with large gas condensate deposits in the Tournai and Visean deposits, significant accumulations of HHVO and maltha were found in thick alluvial sandstones of the Middle Carboniferous. The Kokhanivka deposit is characteristic of the Precarpathian depression, where the Upper Jurassic reefogenic-carbonate paleokarst reservoirs contain HHVO, which are connected by gradual transitions with both conventional oils and malthes.

The results of the analysis of the patterns of phase-geochemical differentiation of naphthides in terrigenous and carbonate complexes of various ages of various oil and gas-bearing basins (OGBs) indicate, firstly, the existence of a fundamental boundary between conventional oils and HHVO, tending to NB, and, secondly, a wide range their paragenetic relationships. At the same time, unlike naphthoid bitumens, which are not related to oil by origin and are products of local impact on organic matter (coal, oil shale, etc.) of elevated temperatures and (or) tectonic stresses in the conditions of contact metamorphism and dynamo-metamorphism, accumulation bitumen-naphthides (including HHVO as a fundamentally important intermediate link) are characterized by the fundamental unity of conditions and processes of formation with oil and gas condensate deposits. This genetic unity is fully consistent with the belonging of oils, HHVO, malthas, asphalts, asphaltites, and ozokerites to oil bitumens.

1.2 Geological conditions of occurrence for heavy HHVO and NB deposits.

Despite the fundamental genetic unity of naphthides, the geological conditions of their occurrence differ in a number of interrelated specific features. Compared to oil and gas, HHVO – NB are characterized by: a significantly higher degree of concentration of global reserves in non-anticlinal structures (the Athabasca field – more than 70%); the presence of two main stratigraphic levels (intervals) of their concentration (Lower Cretaceous – more than 80% of world reserves, Upper Permian

– about 10 %); the presence of well-defined belts (Western Canadian, Orinoak, Olenek, South Tatar, etc.) and nodes of bitumen accumulation.

The most favorable conditions for bitumen accumulation are characteristic of pericratonic troughs and depressions. First of all, this applies to the marginal parts of Precambrian cratons (shields) in the zones of their articulation with geosynclinal belts (fold-orogenic structures) and riftogens (paleooceans, avlakogens). Where oil and gas accumulation processes occur in such tectono-geodynamic situations, the prerequisites for the formation of large bituminous belts in the distal parts of pericratonic slopes with a sedimentary cover reduced due to a series of breaks and unconformities, the presence of several paleohydrogeological cycles, and the repeated activation of crypto- and idiohypergenic processes arise. The main regularities of the accumulation of HHVO – NB in such conditions are illustrated on the examples of the oil and bituminous belts of the Western Canadian, Orinoka, Volga-Ural, Caspian, Timano-Pechora, Leno-Vilyuy oil and gas-bearing provinces. On their basis, the main stratigraphic, (paleo)tectonic, sedimentational-paleogeomorphological, (paleo)hydrogeological and other criteria for forecasting and searching for significant accumulations of HHVO – NB in Ukraine, whose oil and gas-bearing regions are exceptionally favorable for the formation of large oil-bitumen accumulation zones, are defined. The oil and gas-bearing regions of Ukraine, which are characterized by a combination of rift zones and deep domanicoid depressions with extensive monoclinals, are extremely promising from the point of view of discovering significant accumulations of HHVO – NB in complexes of different ages with a wide stratigraphic, tectonic-formational and lithological-facies range. At the same time, their distribution areas can be located outside the industrial oil and gas-bearing territories. The great prospects for the development of this type of unconventional HHVO – NB resources in Ukraine are evidenced both by the set of conditions and laws of naphthidogenesis established here, as well as by the discovery of a number of deposits with clusters of HHVO – NB in the east, west and south.

Favorability of the oil and gas-bearing regions of Ukraine for the formation of significant industrial clusters of HHVO – NB is primarily due to the interaction of moving belts of different tectono-geodynamic nature with the slopes of the Ukrainian shield, as well as with the southern slope of the Voronezh massif (the northern side of the Dnipro-Donetsk avlakogen).

Western oil and gas region. In the Western oil and gas region, the most favorable conditions for the formation of HHVO – NB deposits exist within the limits of the Lviv (Volyn-Podilsk oil and gas region) and Pre-Carpathian troughs. Numerous bituminous manifestations in the form of inclusions and smears of HHVO, maltha and asphalt, as well as veins of hard bitumen are observed in cracks, caverns and secondary pores of Silurian and Devonian carbonate rocks of the Lviv trough. In the area of the Pre-Carpathian trough and its platform framework, accumulations of naphthides of a wide phase-geochemical range of various ages are observed: from solid bitumen, asphalt, maltha, HHVO to dry methane gas.

The oil of the Kokhanivka field is heavy (density 949–992 kg/m^3), highly viscous (viscosity in reservoir conditions 200 MPa·s, viscosity of degassed oil 339 °MPa·s), with a high content of resins (22.2–26.1%), asphaltenes (17.5–21.3%) and sulfur (6.5–7.24%) [5]. Thus, it is a typical HHVO, which is much closer in composition and properties to maltha than to ordinary oils.

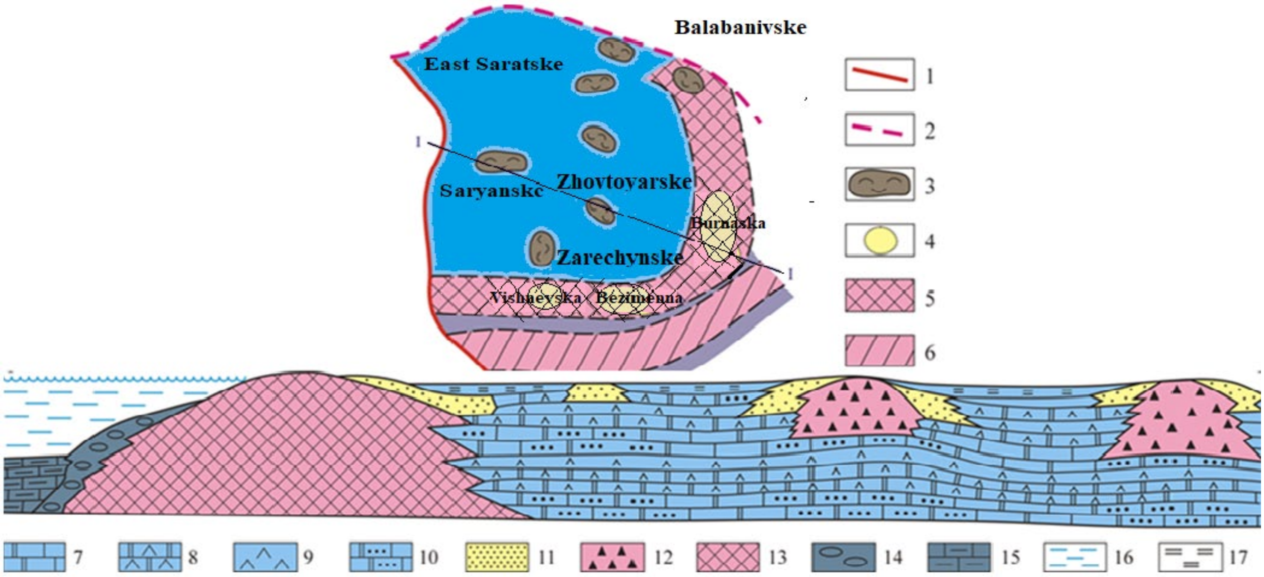
Isotopic-geochemical data indicate the participation of hydrocarbons from ancient (pre-Cretaceous and pre-Paleogene) deposits of the Kokhanivka zone (Stryya Jurassic Trough) in the recovery of sulfates of saline-gypsum-anhydrite layers of the Miocene molasses formation and the formation of a number of sulfur deposits. All this makes it possible to consider the Upper Jurassic reef trends of the area of articulation of the Precarpathian depression and the platform as a zone of ancient oil and bitumen accumulation. Thus, the Inner and Outer oil and gas bearing zones of the Pre-Carpathian trough fundamentally differ in the nature of bitumen formation processes. For young (Pliocene-Quaternary) high-paraffin oil deposits of the Boryslav-Pokut zone, HHVO are generally not typical, not counting the occurrence of heavy (900–920 kg/m^3) with an increased (up to 1–3%) sulfur content near the WOC in Bytkiv - Babchinsk, Boryslav, Blazhivsk fields.

The southern (Azov-Black Sea) oil and gas-bearing region is characterized by a number of different age zones (areas) of oil accumulation in a wide phase-geochemical range. Among them, reefogenic-carbonate zones play a significant role. The most ancient naphthids are located in the Pred-Dobrudzha oil-bearing area within the Biloli tectonic block of the Sarat-Balabaniv fold zone. They are represented by high-sulfur HHVO and are associated with the Paleozoic (S-D–C1) Bilolisk megaatoll (Fig. 1). Within its limits, industrial oil potential was found in the East Saratsk, Yaroslavsk, Zhovtoyarsk and other deposits in the Middle Paleozoic (Eiffel-Lower Visean) sulfate-carbonate formation [6].

Collectors are mainly cavernous desulfated carbonates, fragmented rocks, loose formations of the dolomite and anhydrite «flour» type. With a relatively low density (832–862 kg/m^3), oils are characterized by a high content of resins (10–22%) and asphaltenes (up to 26%), slightly increased sulfur content (0.18–0.85%) and high paraffin content (up to 12%). The wide distribution of bituminous occurrences here in the form of HHVO tides (with a solidification temperature of 25–30 °C), as well as inclusions and smears of malthas, asphalts, hard bitumen in carbonate and terrigenous reservoirs of the Silurian, Devonian, and Lower Carboniferous age allows us to consider the Biloli block as an area of bitumen accumulation of various ages.

The Chadyr-Saratsk Upper Jurassic (Oxforian) reefogenic-carbonate belt, connected with the Chadyr-Saratsk fault, is also considered as a possible bitumen accumulation zone. Numerous oil and gas shows and NB smears (HHVO, malthas, asphalts) contained in biohermic, bioclastic oolitic dolomitized limestones were discovered in individual exploration wells.

Industrial clusters of HHVO are established in the Semenivka, Aktask, Borzovsk and other fields of the Indolo-Kuban OGA. Most of their deposits lie in cracked-cavernous-porous limestones of the Neogene (chokrak, karagan) in the depth range of 190–600 m. The density of oils varies between 901–930 kg/m^3, viscosity – 211–560 MPa·s. These are resinous (up to 12.5%), low-sulfur (<0.15%) HHVO aromatic-naphthenic composition (alkane content up to 11–12%).



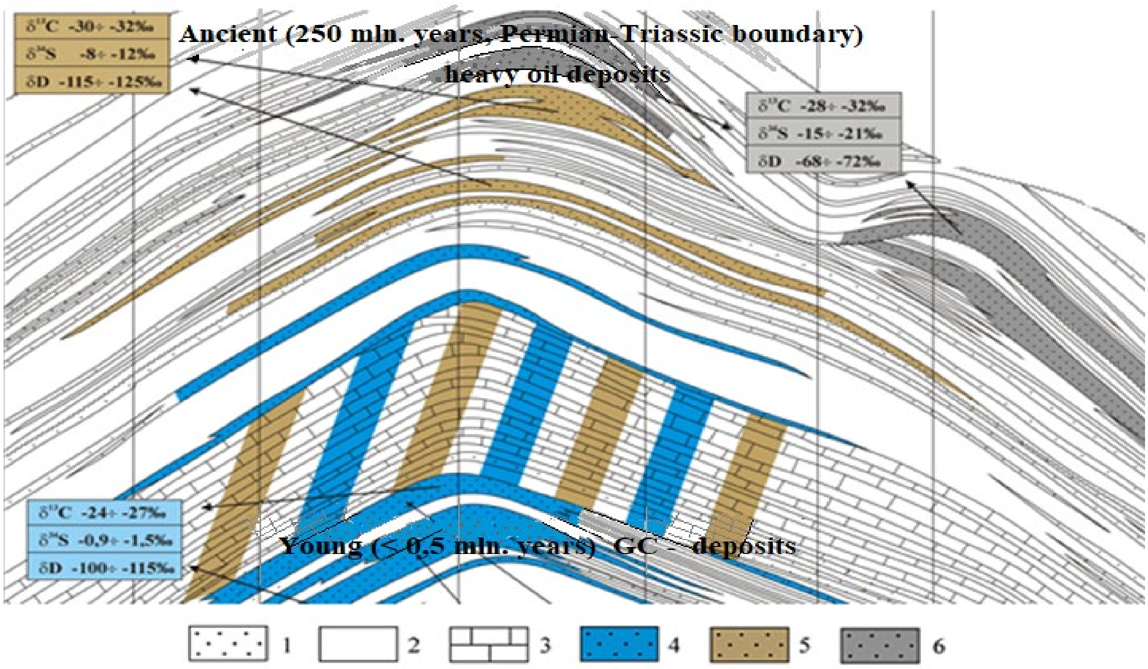
1 – discharge with the lowered western wing (western border of the Bilolisky Block); 2 – a regional fault with signs of thrust formation: mylonitization of rocks – the northern border of the Biloli block; 3 – intra-lagoon algal bioherms to which oil-bearing carbonate reservoirs are confined; 4 – anomalies of intense absorption of seismic energy, possibly associated with oil-bearing reefogenic-carbonate reservoirs; 5 – zone of expected development of the Famennian-Tournaean-Lower Visean barrier-reef carbonate massifs; 6 – the zone of expected development of the Middle Devonian-Fransian barrier-reef carbonate massifs; Submeridional lithological-paleogeomorphological profile (along line I-I): 7 – micro-grained and lumpy carbonate rocks; 8 – dolomites with sulfate inclusions, sulfate-dolomite rocks; 9 – anhydrites; 10 – oolitic dolomites and limestones; 11 – sand-oolite accumulative bodies; 12 – algal (cyanophyte) and bacterial-algal intra-lagoon bioherms; 13 – barrier-reef carbonate massif; 14 – pre-reef debris-carbonate plume; 15 – depressed dark-colored siliceous-clay pelitomo-rf carbonates; 16 – normal sea basin; 17 – lagoon basin with high salinity

Figure 1 – Bilolisk Middle Paleozoic megaatoll (according to O.Yu. Lukin, G.L. Trofymenko)

Eastern oil and gas-bearing region (Dnipro-Donetsk avlakogen). Avlacogens are characterized by favorable geological conditions for the formation of naphthide deposits of a wide phase-geochemical range – from HHVO, maltha, asphalts to higher kerites and anthraxolites [7].

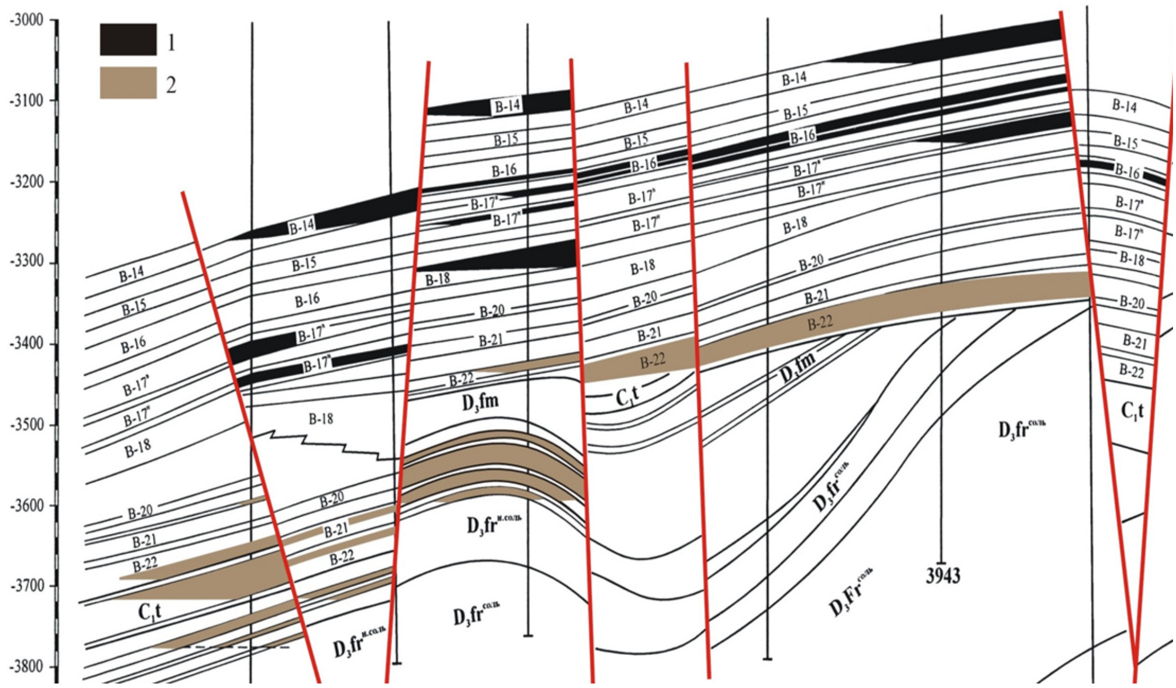
Typical representatives of such deposits are Yablunivka (Fig. 2), Bugruvate (Fig. 3), as well as Bohdanivka, Skorobogatkivka fields and many others. Deposits of HHVO, malt and other NB in these fields lie in paragenesis with oil and gas condensate deposits in a wide stratigraphic range (mainly Carboniferous and Upper Devonian). They are confined to various terrigenous and carbonate reservoirs, the nature of their filling indicates a close genetic connection with conventional oils.

Physico-chemical properties of HHVO, their degree of sulfur content and other parameters vary widely, which is related to the multiphase nature and variety of conditions of their formation [8]. They are characterized by large ranges of fluctuations in density (887–957 kg/m^3), kinematic viscosity (from 7.4 to 4310.2·10^{-6} m^2/s at t = 20 °C), paraffin content (0–13.95%), sulfur (0.1–1.70%), resins (0.44–47.66%), asphaltenes (traces – 27.9%), large variations in the yields of the main fractions.



1 – sandstones; 2 – clay rocks; 3 – carbonate rocks; 4 – deposits of gas condensate; 5 – oil deposits; 6 – deposits of heavy oil and malt

Figure 2 – Yablunivka giant oil and gas condensate field with deposits of heavy oil and malt (according to O.Yu. Lukin)



1 – HHVO; 2 – oil

Figure 3 – Bugruvate field (deposits of heavy and normal oils) (according to R.M. Okrepky)

In addition, deposits of HHVO and maltha are known on Bakhmatka, Tvansk, Kholmske, Velikozahorivka and other areas. The main part of them is related to the Upper Visean various morphogenetic types of sand bodies. The open porosity ranges from 10 to 22%, the permeability reaches $500 \cdot 10^{-3}$ mkm^2, the effective capacity is 5–12 m. HHVO of the Bakhmatka deposit is an opaque, black, highly viscous ($210.6 \cdot 10^{-6}$ m^2/s at t = 50°C) liquid with a density of 911.4 kg/m^3. It is highly resinous (22%), paraffinic (2.5%), moderately sulfurous (0.32%), with a high content of asphaltenes (3.8%) and coke yield (5.9%). Its fractional composition is characterized by a low yield of gasoline fractions (3.5%) and light epaulettes (18.5%). All this testifies to its intermediate nature between oil and maltha. The oil and malts of the other above-mentioned areas of the north-western part of the DDD are characterized by close indicators.

It should be emphasized that there are great prospects for the search for HHVO in the areas of salt diapirs, since there are special conditions for bitumogenesis here. The examples of Romny, Brigadyrivka and other salt shafts, where HHVO inflows were obtained from the shaft breccias, testify to the expediency of considering salt diapirs as specific areas of bitumen accumulation.

In the areas of regional oil and gas potential, to which the central part of the DDD belongs, there are also many ancient deposits of HHVO – NB. But the most favorable conditions for their formation and existence are in the marginal parts of the oil and gas-bearing provinces on the border or outside the industrial oil and gas bearing area. In the DDD, in addition to the extreme northwest and some ancient buried structures, where the already mentioned bituminous-oil-gas-condensate Yablunivka and bituminous-oil Bugruvate fields are examples of objects of complex development of deposits related to them, certain areas are included riparian zones and monoclinal slopes of the Voronezh Massif and the Ukrainian Shield. Among the latter, the prospects of the Lower Carboniferous deposits of Western Donbas and the Starobil-Milleriv monocline, as well as separate areas of Southern Donbas, should be noted.

On the Shulgivka area, an inflow of HHVO was obtained from Upper Visey sandstones in the interval 188–191 m (flow rate 16–18 l/day). Its density is 949–1000 kg/m^3, kinematic viscosity (at 20 °C) 60–70 MPa·s, solidification temperature +20 °C, resin content (sulfuric acid) 19–22% vol., sulfur 0.58%, coke 9.56% wt.

It should be noted that the Eastern region is characterized by the widest, compared to other oil and gas-bearing regions of Ukraine, stratigraphic and lithological ranges of distribution of HHVO, as well as malt and other NB.The formation of most of them is caused by paleohypergenic processes associated with a certain tectono-geodynamic and paleohydrogeological cycle. Therefore, the Eastern oil and gas-bearing region is characterized by an extremely wide phase-geochemical range of naphthidogenesis. This is particularly related to the morphological and chemical diversity of the HHVO – NB deposits, which must be taken into account during their search, exploration and development.

2. Comparative analysis of mining technologies

An example of successful commercialization of technologies for the development of natural bitumen deposits is the activity of Canadian companies Suncor Energy Inc., Albian Sands Energy Inc., and Canadian Natural Resources Limited.

To maintain commercial production rates of heavy oil, measures to reduce its viscosity are almost always necessary. The characteristics of heavy oil are highly correlated with the content of high molecular weight, high density and polar groups such as resins and asphaltenes.

The main methods of developing high-viscosity oil fields are: thermal (influence with water vapor, formation combustion, electromagnetic heating); mixed and unmixed displacement by gaseous agents: (hydrocarbon gases, CO_2, nitrogen, flue gases); chemical: (surfactants, polymers, thinners, microbiological preparations); physical: (influence by physical fields) [9].

At the same time, the main ones are the methods that involve thermal influence (cyclic steam stimulation (CSC), steam flooding (SF), steam gravity drainage (SAGD), hot water flooding, layer combustion, etc.) [10]. The world production of heavy oil is approximately $100 \cdot 10^4$ t/day, of which thermal regeneration exceeds 60%. At the same time, heavy oil produced by steam injection accounts for 80% of thermal oil production [11].

2.1. Thermal methods.

The technology of cyclic steam stimulation (CSS) involves the introduction of high-temperature steam into the formation. Then the well is closed for a certain period. After the thermal energy is transferred to the oil layer, the well is opened for production. The entire CSS process is conducted through a single well. The technology is suitable for heavy oil reservoirs located at a shallow depth (<1000 m) and low viscosity (<50000 mPa·s) [12]. At the same time, the well can be both vertical and horizontal. However, after several production cycles, the amount of extracted oil gradually decreases due to an increase in the water content of the products. At the same time, the oil recovery rate using this technology is only 10–20% [13].

Steam flooding (SF) technology involves injecting steam into one well or a mixture of steam and hydrocarbons, and extracting oil from others. The SF method arose because the CSS technology produces heavy oil close to the well, and the dead zone between the wells is not exploited. The mechanisms of SF are heat transfer and distillation. Components of heavy oil in the contact zone are distilled by steam, which is continuously injected. The distilled components then condense to a liquid upon contact with the cold oil at the boundary of the vapor chamber. Usually used at a later stage of development. The technology makes it possible to increase the oil recovery ratio by 20–30% compared to CSS [14].

However, steam flooding suffers from many limitations, such as severe heat loss in thin-layer formations, significant steam penetration and early breakthrough, and poor economic efficiency. At the same time, high steam injection pressure is required to maintain energy to penetrate deep into formations [15].

Steam Assisted Gravity Drainage (SAGD) is a method of producing heavy oil in which steam is pumped into the formation from a horizontal (or vertical) well located above another horizontal production well in the lower part of the formation. The process begins with the stage of preheating to implement thermal communication between the injection and production wells. The injected steam affects the formation, forming a steam chamber that moves up and sideways and transfers heat to the oil. Heated heavy oil and steam condensate are extracted from the lower horizontal well by gravity [16].

Layers of shallow depth, high permeability, and slight heterogeneity are suitable for operation using the SAGD technology. SAGD technology, for example, is used to extract heavy oil from oil sand deposits. Similar to steam flooding, the SAGD method also has high requirements for steam quality. However, the SAGD method allows to increase oil production by more than 20% compared to cyclic steam injection [17].

However, producing high-temperature, high-quality steam requires significant volumes of water and natural gas. At the same time, the steam chamber gives off a significant amount of heat to the surrounding rock. As a result, the steam-oil ratio (iSOR) is relatively high [18].

2.2. Methods of cold mining.

Significant potential has been demonstrated by non-thermal extraction methods based on solvents, such as cyclic solvent injection (CSI) technology [19]. As a potential solvent, researchers consider gas with high solubility in heavy oil, such as CO2, ethane, propane, n-butane, toluene, as well as solvent mixtures.

A typical cyclic solvent injection cycle consists of three stages: solvent injection, aging, and oil recovery. Due to the high viscosity of heavy oil, the released solvent, turning into a gas phase, is not released immediately, but remains dispersed in the oil in the form of microbubbles, which contributes to its extraction. At the production stage, diluted heavy oil together with the solvent enters the wellbore in the form of a foamy flow. However, the CSI technology is the most economical and effective in the early stages of deposit operation [20].

A proven effective method of increasing oil yield is injection of CO_2 into formations. CO_2 readily dissolves in heavy oil, reducing its viscosity, improving mobility and increasing the final recovery rate. When CO_2 dissolves in heavy oil, its volume increases. This phenomenon not only increases the kinetic energy, but also reduces capillary resistance and flow resistance, thus improving oil permeability [21]. In addition, injected CO_2 can remove oil residues trapped in the pores. Meanwhile, part of the dissolved CO_2 is stored as pressure energy. After the formation pressure is reduced, a lot of carbon dioxide is released from the oil, which displaces the oil and acts as a driving force [22].

However, one of the main technical problems with CO_2 injection is the possibility of asphaltene precipitation.

2.3. Chemical flooding (cold).

Systems of chemical flooding of heavy oil mainly include alkaline flooding, surfactants (surfactants), polymer flooding and their combination [23]. Surfactants (petroleum-soluble and water-soluble) co-injected into formations at low concentrations can significantly reduce oil viscosity and alter interfacial wettability, increasing oil recovery rates. However, they are usually expensive and thermally unstable, which limits their commercial use [24].

Surfactants can emulsify heavy oil to create oil-in-water (O/W) emulsions, with significantly reduced viscosity and significantly improved fluidity. Emulsification and desorption are the two main mechanisms of action of heavy oil cold recovery agents.

2.4. Variants of combined production stimulation.

Many scientists have investigated the feasibility of using CO_2 as an auxiliary agent to promote vapor flooding. Due to the dissolution of CO_2, the viscosity of oil additionally decreases and its volume increases. The result is an increase in oil recovery by 15.6% compared to pure steam [25].

However, CO_2 has a limited effective radius and is only effective in the vicinity of the well. In [26], a new technology for thermal extraction of heavy oil based on supercritical water using CO_2 and N_2 (MGA-SCW) is proposed. The working agent is produced at a pressure of 25 MPa and 400 °C using formation waters containing oil residues (or oil and formation water). As a result of its injection, the extraction rate of heavy oil improves, and part of the CO_2 remains in the formation. At the same time, the working agent is both a heat carrier and an organic solvent [27]. Chemical agents such as alkanes, surfactants, and polymers are also used to improve steam flooding [28].

Surfactants can reduce the oil-water interfacial tension, change the wettability of the rock surface, and increase the fluidity of heavy oil, etc., thereby increasing the efficiency of steam flooding. Compared with other chemical agents, surfactants are the most widely used in thermochemical fluid flooding [29]. The combination of surfactants resistant to high temperatures and thermal extraction methods made it possible to obtain a high level of extraction of heavy oil [30].

Hydrocarbon solvents, the main mechanism of which is viscosity reduction, achieve a much lower level of viscosity reduction compared to water-soluble chemical viscosity reducers, because the latter have greater mobility and form an emulsion of oil in water, which accelerates its filtration in the reservoir. The phase behavior of hydrocarbon solvents plays an important role in reducing viscosity and increasing heat transfer efficiency [31]. As a result, only some hydrocarbons, such as n-hexane and n-heptane, have parameters of phase equilibrium close to the parameters of water at thermobaric parameters of the technological process, and therefore can be used as solvents [32]. At the same time, solvents can dissolve in oil, and, therefore, increase its mobility near the boundary of the steam chamber [33].

The combination of steam injection with a solvent can increase the oil recovery ratio by 20% compared to pure steam injection [34]. However, this method faces the problems of low economic efficiency and high solvent retention in porous media [35]. In addition, in the oil layer, the diffusion time of the organic alkane solvent is much longer than the thermal diffusion time of the vapor, and it is difficult for the vapor and the solvent to form a synergistic effect on reducing oil viscosity [36]. The high cost of the organic alkane solvent also limits its widespread use in oil fields.

In [37], the method of cyclic injection of CO_2 and a viscosity reducer is proposed.

First, a viscosity reducer soluble in petroleum products is injected into the formation, after which CO_2 is injected. During 15 days of exposure, CO_2 and viscosity reducer diffuses throughout the formation. The viscosity of heavy oil is significantly reduced, mobility is improved. After the aging period, extraction begins.

In [38], a comprehensive approach using naphtho-soluble viscosity-reducing agents and steam injection mixed with CO_2 (DCS) is proposed. As a result of the diffusion of reagents and the action of gravity, the efficiency of flooding improves, and the viscosity decreases as a result of the formation of an emulsion. In addition, due to the difference in the density of CO_2 and steam, CO_2 accumulates in the vault of the formation. This slows down heat loss in the vertical direction. Thus, this method intensifies the extraction of heavy oil by increasing the efficiency of the macroscopic drainage zone and increasing the efficiency of microscopic displacement [39].

The work [40] describes a process that involves a combination of continuous CO_2 injection with a holding stage for its dissolution in oil (CO_2-SAG). In the first stage, CO_2 is continuously pumped into the formation in the same way as in the traditional process. The CO_2-SAG process differs from conventional CO_2 injection in that it stops at breakthrough. The second stage of the CO_2-SAG process is the aging period. During this period, the CO_2 diffuses into the oil and water in the formation that the gas did not contact during the first dynamic stage of the process. In the third stage, another portion of CO_2 is injected to displace the remaining oil that was released during the aging stage.

Steam heating, gas to increase reservoir energy, oil swelling, interfacial tension reduction, hydrocarbon extraction, and chemical emulsification to reduce oil viscosity are the main mechanisms of combined CO_2-chemical and steam flooding [41].

Solvent-enhanced SAGD (ES-SAGD) technology has been very successful in improving production in Canada. At the chamber boundary, the mixture of vapor and solvent condenses. The steam transfers its latent heat to the bitumen and the solvent dissolves, diffuses into the bitumen and lowers its viscosity below that which can only be obtained with steam. Based on phase equilibrium, a second hydrocarbon liquid phase can exist at the edge of the vapor chamber. However, this solvent-enriched liquid phase will only occur at high solvent concentrations exceeding those predicted in the ES-SAGD process [42].

One of the main tasks of the process is to recover as much of the injected solvent as possible for its reuse. In 2002, PanCanadian launched a solvent-based pilot process (SAP) in Senlac, Saskatchewan. Shortly after the start of butane injection, the flow of oil increased by more than 50%. At the same time, the yield of the solvent was more than 70% [43]. In the Cold Lake, Alberta project, the solvent was injected into wells during the late cyclic steam stimulation (CSS) stage of the Imperial Oil Liquid Addition to Steam for Enhanced Recovery (LASER) pilot process [44]. Bitumen production rate increased by 100%. The solvent yield exceeded 80%.

2.5. Catalytic aquathermolysis.

Methods based on steam stimulation are effective for the operation of conventional heavy oil, but less effective when working with extra heavy oil. Steaming has a limited effect on reducing the viscosity and improving the composition of the oil. As it is mentioned above, a number of problems arise during its use. In addition, due to polymerization and condensation reactions, steam injection leads to an increase in the viscosity of extracted oil on the surface [45].

At the same time, the effectiveness of thermal exposure methods can be increased by promoting destruction reactions. Under the influence of steam at a temperature in the range of 200–300 °C, the viscosity of heavy oil can be significantly reduced, the content of resins and asphaltenes is clearly reduced, and the content of saturated and aromatic compounds is noticeably increased. At the same time, a decrease in the viscosity of heavy oil/bitumen occurs not only due to the effect of high temperature, but also due to a number of chemical reactions of aquathermolysis. These reactions occur between components of steam, sand and oil [46].

These processes lead to the breaking of some bonds (primarily aliphatic sulfur bonds) and the lightening of complex oil molecules in the presence of water and at high temperature. The main effects of aquathermolysis are a decrease in the content of asphaltenes and resins, an increase in saturated and aromatic compounds, a decrease in molecular weight, a decrease in sulfur content, an increase in the H/C ratio, and a decrease in the viscosity of extracted oil [47].

At the same time, in the process of aquathermolysis, the efficient productivity of the enrichment of heavy oil in place and the reduction of the consumption of fresh water for the production of steam can be achieved with the introduction of catalysts. Covalent chemical bonds between C-S, C-O, and C-N bonds, except for some C-C bonds at lower temperatures, are easily broken during the catalytic aquathermolysis process [48]. Therefore, in recent years, catalytic modernization has become an important area of research for solving some problems that arise during the production of heavy oil. Transition metal compounds have a catalytic effect on the breaking of C-S bonds [49].

Today, the technology of catalytic aquathermolysis is considered one of the most promising technologies for the production of heavy oil. The main effect of aquathermolysis is the destruction of the complex structure of asphaltene and resins. Catalysts based on nickel and iron led to their transformation into gaseous components, saturated, aromatic compounds and resins. The gas mixture contained H_2, CO, CO_2, H_2S and light hydrocarbons [50].

3. Research results

Due to the properties of heavy oil/bitumen, namely high viscosity and low fluidity, the thermal recovery method is widely used throughout the world. Cyclic steam stimulation, hot water and steam injection, gravity drainage with steam, and in situ combustion are the most advanced thermal methods. At the same time, an alternative to methods of improving the characteristics of heavy oils directly in the formation is catalytic aquathermolysis. However, thermal methods are effective for shallow and thick formations. They are limited by appropriate equipment and a complex operation process.

In Ukraine, a significant amount of retrograde gas condensate fell out in the reservoirs of gas condensate deposits due to a decrease in formation pressure. Its extraction is extremely difficult. During the research, the effectiveness of the catalytic destruction of the components of the gas-condensate mixture was experimentally confirmed. Stable autocatalysis was recorded after increasing the temperature of the mixture to 150°C. The result of the process was the formation of C_1-C_4 alkanes, an increase in the yield of the C_6-C_{16} fraction, a decrease in density, kinematic viscosity and average molecular weight. The results of the study are shown in table. 1.

Table 1 – Results of the evaluation of the effectiveness of the catalytic destruction of gas condensate of the Zagoryansk gas condensate field of well № 3 at a pressure of 7.3 MPa in samples with a porosity of 15% by volume

The temperature of the experiment, °C and the presence of a catalyst in the core	Fractional composition		Density, kg/dm^3	Viscosity, sst	Volume of the driven sample, % vol.	Molecular weight	Permeability, mD
	% vol.	°C					
120 -	BC 50.0 90.0 EC	72 170 297 303	0.829	42	90	249	2.76
120 +	BC 50.0 90.0 EC	60 164 282 287	0.825	34	90	173	7.54
120 +	BC 50.0 90.0 EC	47 126 249 261	0.812	17	96	104	40.35
150 -	BC 50.0 90.0 EC	72 170 297 302	0.829	43	89	252	2.19
150 +	BC 50.0 90.0 кк	56 154 280 285	0.823	34	90	169	8.04
150 +	BC 50.0 90.0 EC	43 121 247 257	0.810	15	96	94	42.64
200 -	BC 50.0 90.0 EC	70 168 293 296	0.822	40	90	235	2.75
200 +	BC 50.0 90.0 EC	51 149 277 292	0.815	23	95	114	38.1
200 +	BC 50.0 90.0 EC	27 139 266 275	0.798	11	98	78	100.25

The effectiveness of the catalytic method of influence was also confirmed during research and industrial tests conducted on well 79 of the Kotelva gas-condensate field, which was inactive due to the fall of retrograde condensate: 20.000 m^3/day of gas and 3 m^3/day of condensate were obtained. Product characteristics for processing: the beginning of condensation (BC) – 71 °C, 10% – 118 °C, 20% – 139 °C, 30% – 162 °C, 40% – 183 °C, 50% – 203 °C; end of condensation (EC) – 356 °C, kinematic viscosity – $1.74 \cdot 10^{-3}$ Pa s at 20 °C, density – 793 kg/m^3, molecular weight 219 units. Product characteristics after processing: BC – 35 °C, 10% – 50 °C, 20% – 60 °C, 30% – 74 °C, 40% – 78 °C, 50% – 82 °C; EC – 118 °C, kinematic viscosity – $0.273 \cdot 10^{-3}$ Pa·s at 20 °C, density – 703 kg/m^3, molecular weight 79 units.

4. Conclusions

The accumulation of HHVO and NB is an intermediate link between traditional and unconventional sources of hydrocarbons. This determines the expediency of connecting this special type of naphthides to the development of oil and gas fields.

In our country, there are all geological and (paleo)hydrogeological factors for the formation of «hybrid» deposits of the type of Yablunivka and Bugruvate with a wide phase-geochemical range of oil deposits, which must be taken into account when planning the development of such deposits. Prospects for searching for bituminous belts should be associated with the peripheral parts of the Eastern and Western oil and gas-bearing regions.

The most favorable paleogeographic and paleohydrogeological conditions for the formation of HHVO – NB are characteristic of the Northern and Southern sides of the Dnipro-Donetsk oil and gas-bearing region, as well as its northwestern segment, where clusters of HHVO are exposed in Bakhmatka, Tvansk and other areas. According to the specified criteria, there are grounds for the existence of large bituminous belts on the Volyn-Podilsk edge of the East European platform in the pericratonic subsidence zones of the Ukrainian shield and its articulation with depressions. In particular, this concerns terrigenous deposits of the Upper Proterozoic and Cambrian, as well as Silurian reefs of the Dniester pericraton, Devonian and Lower Carboniferous sandstones of the Lviv trough. Here, as well as on the sides of the DDD, as well as in the northern and southern outskirts of Donbas, heavy oil and bitumen should lie in paragenesis with gas and oil deposits.

Based on the distribution of naphthides in the Svidnytsky – Kokhaniv deposits and data from other deposits, a large oil-bitumen belt associated with the Upper Jurassic barrier reef is notable. It lies under the Neogene zone of intensive gas accumulation (Bilche-Volitsk zone of the Pre-Carpathian trough).

As it was noted many years ago [1], according to minimum estimates, the forecast resources of HHVO – NB in the bowels of Ukraine amount to 0.5–1.0 billion tons. At the same time, reserves of HHVO are growing at the expense of residual oil from traditional fields as they are depleted. In carbonate and terrigenous reservoirs, residual oil and condensate represent a significant additional reserve of liquid hydrocarbons for Ukraine. For example, a comparison of extraction coefficients and the volume of extracted oil (depending on the region, other properties of reservoir and oil, as well as the percentage of paraffins, it lies within 15–60%) allows to forecast resources of retrograde condensate and residual oil only on existing deposits in more than 500 million m^3 [1].

The above data and taking into account the foreign experience of extracting hydrocarbon raw materials through the development of HHVO – NB deposits allows us to assess the prospects of this area of development of the hydrocarbon potential of Ukraine's subsoil at a sufficiently high level.

Taking into account the features of the occurrence and distribution of high-viscosity oil/bitumen deposits on the territory of Ukraine, the volume of resources, as well as a wide range of their physical and chemical properties, it is proposed to foresee the following strategy for their development:

1) it is advisable to distinguish two types of deposits according to the depth of their occurrence: the first – within 200–500 m, the second – 800–500 m;

2) SAGD technologies and their modifications will be acceptable (maximum effective) for the first type of deposits. For the second - the technology of cyclic vapor-gravity drainage. At the same time, in both cases, options for combining these methods with catalytic aquathermolysis processes should be provided. Such combinations, for example, can be injection of a catalyst in a mixture with CO_2, N_2, solvents, steam; simultaneously with the processes of formation combustion and hydraulic fracturing of the formation. It is also advisable to provide options for applying catalysts of this process to downhole filters, lift pipes, as well as the mineral skeleton of the formation.

In addition, an important direction is the extraction of residual oil and retrograde gas condensate at the final stage of development of oil and gas condensate deposits. Therefore, it is advisable to simultaneously implement the technologies described above to extract these hydrocarbons.

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ПЕРСПЕКТИВИ ОСВОЄННЯ ВУГЛЕВОДНЕВОГО ПОТЕНЦІАЛУ ПОКЛАДІВ ВАЖКИХ ВИСОКОВ'ЯЗКИХ НАФТ, НАФТОВИХ БІТУМІВ, ЗАЛИШКОВИХ НАФТ ТА ВИПАВШОГО КОНДЕНСАТУ В НАДРАХ УКРАЇНИ

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Анотація. Вуглеводневий потенціал важкої високов'язкої нафти і природних бітумів (мальти, асфальти, асфальтити) залишається практично не освоєним і невизначеним. При цьому, нафтогазоперспективні площі складають понад 80% території України. Також, важливим джерелом вуглеводнів є невидобувні запаси залишкової нафти та ретроградного газового конденсату. Виходячи з цього, метою роботи було обґрунтування технологій їх розробки. Об'єкти дослідження – геологічні умови залягання важких високов'язких нафт і нафтових бітумів в Україні та перспективні технології їх розробки. На основі поглибленого аналізу особливостей утворення, залягання і розповсюдження покладів важких високов'язких нафт і нафтових бітумів, а також аналізу існуючих способів їх видобутку, в роботі вирішувалась проблема вибору максимально ефективних технологій розробки для родовищ України. Оскільки, за результатами аналізу, в Україні поклади важких високов'язких нафт і нафтових бітумів відкрито в інтервалах залягання 800–1500 м і 200–500 м (мілкозалягаючі поклади в складі піщаних відкладів), запропоновано для даних інтервалів, як найбільш ефективні, відповідно технологію циклічної парової стимуляції в комбінації з каталітичним акватермолізом. На даний час в Україні поклади високов'язких нафт і природних бітумів не розробляються і, більше того, їх ресурси мають вкрай низьку геологічну вивченість. Тому, пілотні проекти їх розробки запропоновано реалізовувати в на вже облаштованих нафтових родовищах. Вибір даних технологій обґрунтовано наступним чином: 1) технологію циклічної парової стимуляції в комбінації з каталітичним акватермолізом доцільно реалізувати на вже облаштованих родовищах де ведеться видобуток, але коефіцієнт вилучення важкої нафти є низьким (при мінімальних інвестиція і максимальною рентабельністю); 2) з огляду на накопичений досвід розробки покладів бітумінозних пісків (Альберта, Канада) і маючи в Україні ряд перспективних аналогічних за глибиною залягання і типом покладу родовищ можливий варіант реалізації технології парогравітаційного дренажу або його модифікацій.

Ключові слова: важка високов'язка нафта, нафтовий бітум, технології видобутку, циклічна парова стимуляція свердловинний гідровидобуток, каталітичний акватермоліз.