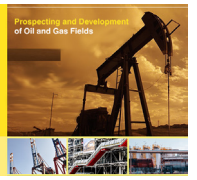
Vol. 24, No. 2
2024



PROSPECTING AND DEVELOPMENT OF OIL AND GAS FIELDS

https://pdogf.com.ua/en

Received: 06.08.2024. Revised: 01.11.2024. Accepted: 29.11.2024

UDC 622.276.34

DOI: 10.63341/pdogf/2.2024.30

# Peculiarities of late-stage development of oil fields in Ukraine and ways of increasing oil production

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**Abstract.** The relevance of the study lies in identifying typical stages of oil field development and determining the beginning of the late-stage period based on the actual values of annual and accumulated oil production and water cut of well products. The purpose of the research was to identify the main features of the late stage of development and to develop technical and economic directions and measures to stabilise and increase oil and gas production. The paper analysed the possibilities of increasing domestic oil production in Ukraine by using the resource potential of fields whose reserves are classified as hard-to-recover. The authors formulated the criteria by which individual deposits and fields contain hard-to-recover reserves and determined the structure of such reserves, taking into account the elements of residual oil saturation of the pore space. The peculiarities of late-stage field development in terms of the dynamics of changes in development indicators were determined. The geological, industrial, economic, social and environmental problems accompanying the development of fields at a late stage were considered. Using the example of the development of the oil industry in Ukraine, the article analysed typical stages of field development and oil and gas production. The structure of oil reserves classified into active reserves, which are extracted mainly through natural reservoir energy, and hard-to-recover reserves, which require the use of targeted artificial stimulation of the reservoir system using various targeted methods and technologies, was presented. A procedure for determining the beginning of the late stage of field development based on the curves of actual accumulated oil production and water cut of well products was proposed and demonstrated using real actual data. The location of the residual hard-to-recover reserves in the oil-saturated pore space was identified. Based on the available average statistical information, the defining features of the late stage of development were comprehensively

**Suggested Citation:** Doroshenko, V., Titlov, O., Kuper, I., & Doroshenko, V. (2022). Peculiarities of late-stage development of oil fields in Ukraine and ways of increasing oil production. *Prospecting and Development of Oil and Gas Fields*, 24(2), 30-37. doi: 10.63341/pdogf/2.2024.30.

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disclosed, which are grouped into geological, technological, organisational, economic, financial, social and environmental. The main areas of activity of research and development and oil and gas companies to address the problem of stabilising and increasing oil production at the late stages of field development were identified

**Keywords:** oil fields; development indicators; hard-to-recover reserves; residual oil; oil recovery; production increase

## Introduction

In the current energy situation in Ukraine, which is characterised by growing demand for hydrocarbons and limited opportunities to discover new large fields, the issue of optimising oil production is extremely important. This is especially true for fields that are at late stages of development, when their natural production potential is significantly reduced and the economic viability of operation requires the implementation of additional technical and technological measures. The late stage of oil field development, which occurs after the stage of maximum production, is characterised by a slow decline in production, high water cut and the need to apply effective methods to maintain technological and economic efficiency of production. Ukraine, which has limited domestic hydrocarbon reserves, is largely dependent on energy imports, which requires special attention to the efficient use of the resource potential of existing fields. The majority of Ukraine's oil fields are in the fourth or late stages of development, with over 90% of wells operated by mechanised production methods and a significant decline in average well production rates. In such circumstances, it is particularly important to develop and implement targeted oil recovery technologies that will increase production volumes and extend the life of the fields. Late-stage field development is also accompanied by problems that cover not only technical but also economic, environmental, social and ecological aspects. Loss of equipment integrity, increased levels of gas pollution, and physical 'aging' of industrial facilities create additional problems for both the economic performance of enterprises and environmental risks.

A number of publications have been devoted to the study of the late stage of oil field development. Their main focus is to consider individual fragments of the field development process without generalising them as a whole. The works of I. Petrenko *et al.* (2021) and V. Moiseiev (2023) mainly covered the issues of the state of production indicators and methods of stimulating hydrocarbon inflow into wells, limiting water flow paths, and levelling the injection profile in injection wells. In particular, scientists I.M. Petrenko *et al.* (2021) identified ways to improve the economic efficiency of oil production enterprises. V. Moiseiev (2023) noted that one of the problems is the lack of oil refining capacity. Almost all oil refineries (about 10) have been shut down since independence, with the exception of two – Kremenchuk and Shebelynka. However, the war between Russia and Ukraine has had serious consequences for them. The study by I. Cuper & A. Uhrynovskyi (2018) presented the structure forms and components of pore space saturation. The authors discussed the physical and chemical characteristics of reservoir hydrocarbons and water, phase changes in hydrocarbon systems, surface and molecular processes occurring at the interface. The article also explained the parameters of hydrocarbon recovery, energy states and operating modes of oil and gas reservoirs, physical fundamentals, and the use of advanced methods of oil and gas condensate recovery.

The paper by A.A. Isaev *et al*. (2022) provided information on methods of stabilising oil production, reducing water cut and preventing its growth, as well as on traditional methods of increasing development efficiency. The paper also presented a set of measures aimed at improving the efficiency of the Zarechnoe field development in the Republic of Tatarstan. M.U. Tahir *et al*. (2023) modelled a number of strategies using water, gas and chemical injection methods to improve production results: they analysed methods of enhanced oil recovery by gas injection, thermal and chemical treatments of the reservoir system. The researchers presented a reliable, comprehensive screening method aimed at optimising the production of "old" oil fields.

The above studies lack a comprehensive approach to solving the problem of increasing oil production at the late stage of development, taking into account economic and environmental indicators. Efficient operation of late-stage fields requires the use of innovative technologies, such as flow-deviating methods, infill drilling, aquifer plugging, and elimination of leakage in the wellbore space. The aim of this study was to identify the defining features of the late stage of oil field development and to formulate technical, economic and geological and industrial measures that will help stabilise and increase oil production. The focus is on hard-to-recover reserves, for which traditional methods are not always effective.

## Materials and Methods

This paper provided a detailed analysis of all active oil fields in Ukraine that are at a late stage of development according to the State Committee of the Oil, Gas, and Oil Refining Industry of Ukraine (1997) and M. Ivaniuta (1998). The most attention was paid to the fields that are on the balance sheet of the main oil producing company, Public Joint Stock Company Ukrnafta (PJSC Ukrnafta), and are among the most important sources of hydrocarbon production in Ukraine, such as Hlynsko-Rozbyshivske, Bugruvativske, Leliakivske, Hnidentsivske, Dolynske, Bytkivske, and Boryslavske. These fields were selected based on high oil production, water cut and the presence of residual hard-to-recover reserves, which is typical for the final stage of development.

The available information on production volumes, flow rates and water cut rates was grouped into several categories based on key geological, production and technological characteristics. This grouping made it possible to determine the structure of the remaining oil reserves that require

special methods for their recovery. The main criterion indicators are based on those specified by V.S. Boyko *et al*. (1996), V.S. Boyko (2012) and V.P. Gryshanenko *et al*. (2015): the level of water cut of well products, which is one of the indicative factors of the late stage of oil field development; the type and structure of residual oil saturation of the pore space, which determines the potential of undeveloped hard-to-recover reserves; distribution by types of reserves, in particular, the allocation of active reserves produced under natural conditions and hard-to-recover reserves that require the use of targeted stimulation methods.

To build the architecture of the main features, a set of parameters reflecting typical characteristics of the late stage of development was formed. They include the following groups of indicators: geological (structure of residual reserves, pore space heterogeneity, presence of low-permeability layers); technological (well operation methods, flow rates, water cut); economic (production cost, profitability, investments in the implementation of production stimulation methods); environmental (level of environmental pollution). Initial information was collected from the following sources: State Committee of the Oil, Gas, and Oil Refining Industry of Ukraine (1997) and V. Moiseiev (2023), which contain data on the total number of oil fields, dynamics of oil, gas and water production. Scientific and technical literature listed in the references was also used. Microsoft Excel was used for statistical analysis and modelling, which made it possible to group data, build water cut and cumulative production graphs, build an architecture of late-stage development features and determine its beginning in technological and time space. Thus, an integrated approach that combined statistical analysis and geological modelling made it possible to assess the state of late-stage development of the fields and propose specific measures to improve the efficiency and completeness of oil production.

## Results and Discussion

Ukraine does not have sufficient domestic oil reserves. There is also no reason to assume that it will be provided with sufficient oil in the future (Lukin, 2008; Vytvytskyi & Pilka, 2016). According to V. Moiseiev (2023), in 2020, there were 216 oil fields in Ukraine, of which 193 were very small with oil reserves of up to 1 million tonnes. There are 21 fields with small reserves (1-5 million tonnes), Bugruvativske field with small reserves, and Hlynsko-Rozbyshivske field with medium reserves (5-30 million tonnes) (State Committee of the Oil, Gas, and Oil Refining Industry of Ukraine, 1997; Ivaniuta, 1998). About 45% of the total well stock operates with weighted average flow rates of up to 1 tonne per day and produces about 3% of oil from the total production. An analysis and summary of the development of the oil industry in Ukraine, based on the example of the largest oil and gas company PJSC Ukrnafta (produces 86% of oil, 28% of gas condensate, and 16% of gas from total hydrocarbon production in Ukraine), shows that it has passed the period of maximum production, which is inevitably followed by a decline (Lukin, 2008; Vytvytskyi & Pilka, 2016). Figure 1 shows the dynamics of annual and cumulative oil production and water cut rates, built by the authors based on actual data of PJSC Ukrnafta, which has a classical character similar to the world oil production curve proposed by K. Hubbert (1956).

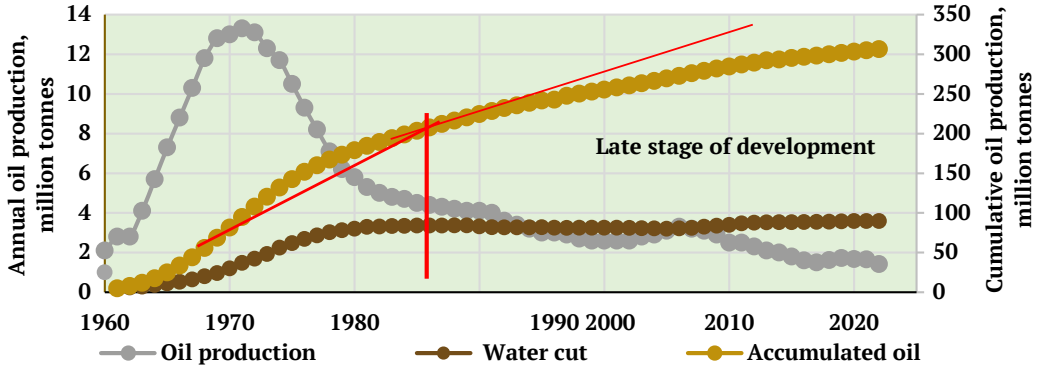


**Figure 1.** Dynamics of oil production and water cut of well products by fields of PJSC Ukrnafta

**Source:** created by the authors based on actual data of oil extraction enterprises

The decline in production is mainly due to intensive depletion of reserves at the main fields and their transition to the late stages of development. The maximum annual oil production was achieved in 1972 due to the discovery and accelerated development of relatively large fields with significant reserves, such as Hlynsko-Rozbyshivske, Bugruvativske, Korzhivske, Leliakivske, Hnidentsivske (eastern region), Dolynske, Pivnichno-Dolynske, Strutynske, Oriv-Ulychnianske, Starosambirske (western region) and others (State Committee of the Oil, Gas, and Oil Refining Industry of Ukraine, 1997; Ivaniuta, 1998; Gryshanenko *et al.*, 2015). Since 1972, oil production has been steadily declining. In 1976-1982, the rate of decline was 8.5-12%, in 1985-1991 – 2.0-2.2% per year. After 1992, these rates increased to 5-10%.

There are four stages of oil field development (Boyko *et al.*, 1996; Oil and Gas Institute, 2004; Gryshanenko *et al.*, 2015). Figure 1 identified these stages as: I – increasing oil production; II – stable production; III – declining production; IV – late stage, which is the longest and is characterised by low, slowly declining levels of oil production,

high water cut of wells, and their conversion to mechanised methods of operation. In Ukraine's late-stage fields, about 90% of wells are operated with pumps of various types and sizes, and about 70% of wells have oil production rates of up to 2 tonnes per day.

The first three stages constitute the main development period lasting, as a rule, 25-30 years, during which 70-85% of recoverable oil reserves are extracted, the remaining 15-30% of recoverable reserves are extracted at the IV or late stage. The authors propose to determine the conventional beginning of the late stage by the curves of accumulated oil production and water cut, which, according to the graphic construction, for Ukrnafta's fields corresponds to 2008 (Fig. 1). The predominant share of oil reserves produced at the late stage of development consists of hard-to-recover reserves (Fig. 2), the extraction of which requires diverse and unique methods and technologies of impact on the reservoir system.

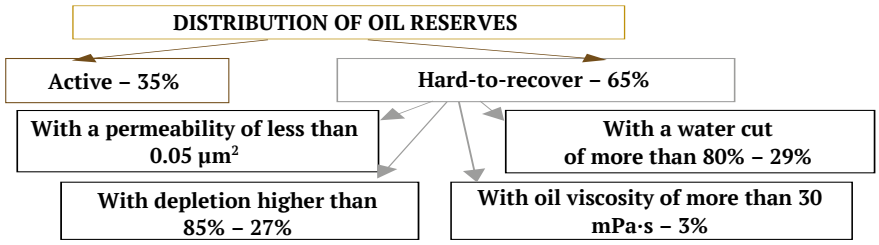


**Figure 2.** Qualitative characteristics of recoverable reserves

**Source:** created by the authors based on T.D. Van Golf-Racht (1982), V.S. Ivanyshyn (2003), I.M. Cuper & A.V. Uhrynovskyi (2018)

When solving the problems of developing fields at the fourth stage, its residual reserves should not be completely equated with the hard-to-recover reserves of new fields with great depths and complex geological structure. The reserves of late-stage oil deposits can be considered extremely hard to recover in terms of their qualitative characteristics and their architecture is partly a consequence of previous technological actions, the imperfection of the development system, waterflooding system, well tapping and development methods, and operating modes.

The hard-to-recover reserves (Fig. 2) include reserves that are not fully recoverable due to: low water displacement capacity; unevenness of the displacement front; heterogeneity of the structure and reservoir properties of the pore space; clogging of pore channels and their compression; presence of low-permeability layers not covered by waterflooding; high rates of extraction from high-permeability layers; location of oil residues in the inter-well areas in conditions of insufficient well grid density and formation of interference zones; accumulation of oil in peripheral undrilled areas with a small oil-saturated thickness, in low-permeability surface or bottom areas, in thin-layer oil rims. These reasons are also mentioned in V.O. Fedorishyn (2005), M.I. Yurkiv (2008) and A.Y. Dandekar (2013).

The late stage of field development is also characterised by the fact that oil production revenues are insufficient to maintain industrial communications and field infrastructure in a functional state, as already noted by such scholars as D.O. Yeher *et al*. (2005), Ya. Vytvytskyi (2008) and I.M. Ivanchenko (2011). This requires a critical review of both technological and economic approaches to facilitate the cost-effective recovery of remaining oil reserves and achieve the design oil recovery factor. In the technological aspect, the efforts of the subsoil user at the late stage of development are aimed at increasing the rate and completeness of the production of residual reserves, the structure of which, according to average data, is shown in Figure 3.

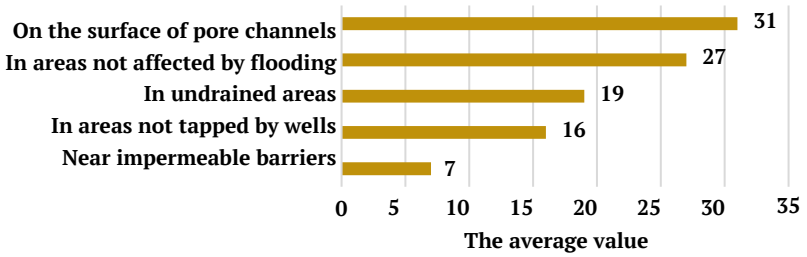


**Figure 3.** Residual oil location in the pore space

**Source:** created by the authors based on T.D. Van Golf-Racht (1982), V.O. Fedorishyn (2005), V.P. Gryshanenko *et al.* (2015)

The authors formulated and grouped the main groups of features that determine the state of the late stage of development as geological and industrial, socio-economic and environmental (Fig. 4).

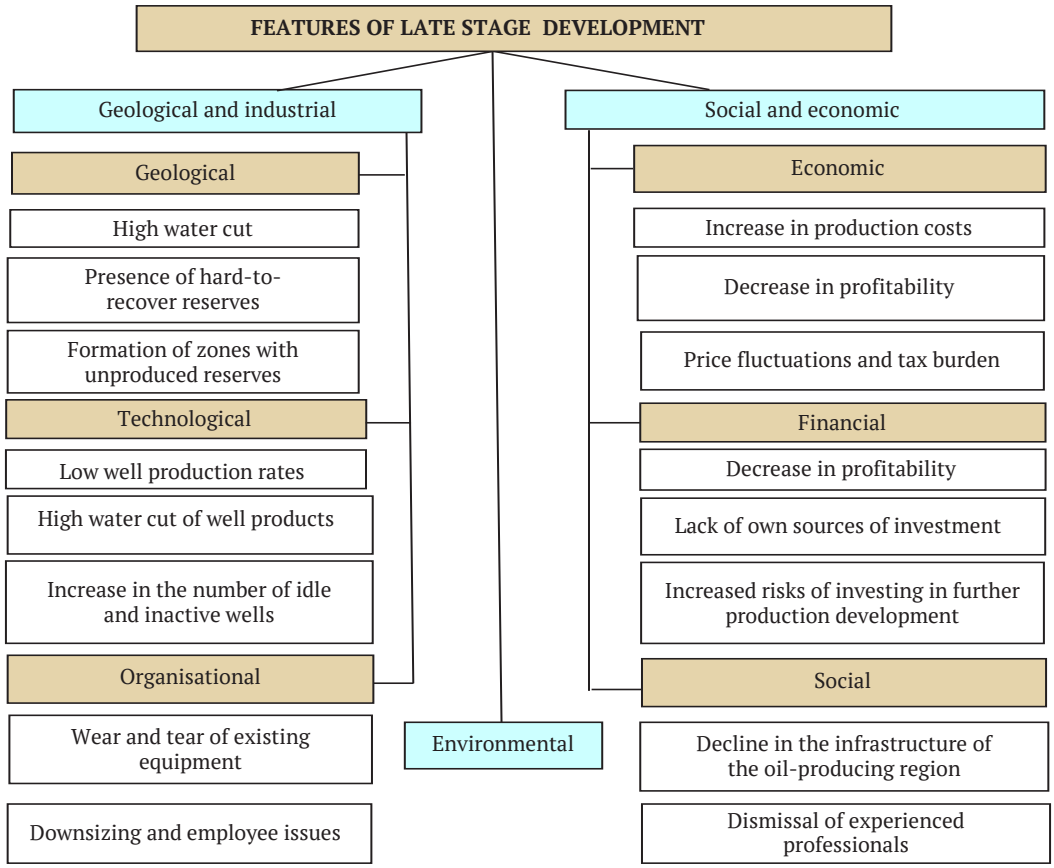


**Figure 4.** The main groups of features of the late stage of oil field development

**Source:** created by the authors

Taken together, these features are decisive in the formation of objects and directions of investment activity of enterprises that operate deposits at a late stage of their development, but the leading one is the geological and industrial group, the state and development of which determines the form and content of social and economic activities. Environmental factors are also important, caused primarily by physical "aging" of underground and surface equipment and loss of its integrity, formation of springs, increased level of environmental pollution, and environmental degradation, as is the case in the fields of Western Ukraine and Poland, as described in Oil and Gas Institute (2004) and I.M. Ivanchenko (2011). One of the main problems of late-stage oil field development, which is the case for the majority of fields on the European, American and East Asian continents, is the identification of the defining features of the stage in order to develop technical and economic measures to stabilise and increase oil production.

Summarising the geological and filtration-capacitive characteristics of oil field reservoirs, physical and chemical properties of fluids and thermobaric conditions that accompany late-stage development processes, the authors, as well as partially V.P. Gryshanenko *et al.* (2015), identifed the following. The deployment of targeted industrial and scientific research is aimed at determining the location and assessing the volume and structure of residual oil in the subsoil. It is necessary to create geological, technical and filtration-capacitive models of oil-saturated objects, while distinguishing different types of residual reserves. A systematic approach to organising the impact on the bottomhole zone, filter and wellbore is aimed at integrating these elements into a single hydrodynamic well formation system to increase well productivity and reduce water cut of the produced product. The optimisation of waterflooding systems should include adjusting the operating modes of injection wells and coordinating their operation with production wells. The use of flow deflecting technologies can improve the efficiency of hydrocarbon production processes. Polymer flooding is required to seal wells of complex architecture, including multilateral wells with horizontal boreholes and productive reservoir opening in depression or equilibrium mode, and is an important step in the process of efficient production. It is necessary to refuse abandonment of wells if their technical condition is acceptable, and to consider the possibility of using them in intermittent operation or as injection or observation wells.

In this direction, with the participation of the authors V.P. Gryshanenko *et al*. (2015), the principles and technologies of systematic targeted isolating and stimulating effects on the bottomhole zone, filter, wellbore, pay zone and interwell zones of the reservoir have already been developed. A number of methods and technologies have been elaborated to develop oil reservoirs, limit the inflow of formation water and eliminate leakage in the wellbore space

of injection and production wells, as well as modern approaches to reinterpreting the results of seismic and geophysical surveys of wells and building permanent hydrodynamic models of hydrocarbon deposits (Boyko *et al.*, 1996; Oil and Gas Institute, 2004; Gryshanenko *et al.*, 2015).

A.A. Isaev *et al*. (2022) also noted that intensification of residue recovery from fields at a late stage of development is one of the most difficult and at the same time urgent tasks for the industry. In particular, the authors noted a possible increase in water cut at the third and fourth stages of development. Intensification of hydrocarbon inflow into a well was also considered by Y.D. Kachmar *et al*. (2004). The implementation of organisational tasks in the current study is to develop appropriate industry programmes and regulations to streamline production activities at the late stage of field development. There is a need for a mandatory recalculation of oil reserves and preparation of projects for the completion of fields, enhanced control and regulation of relations between the state and subsoil users, ensuring conditions for attracting investments and reducing the risks of implementing programmes to improve field development systems and implementing measures to increase oil recovery. When addressing social issues, it is necessary to take into account the presence of developed infrastructure at the fields, highly qualified production and technical personnel, whose downsizing should be carried out mainly on the basis of age and disciplinary principles, possible deterioration of the environmental balance and strengthening of the relevant permanent control.

Financial and economic problems are subject to the principles of increasing technical and technological risks against the background of rising production costs, decreasing cash flows, lower profitability and reduced opportunities for own investments. This was also noted by D.O. Yeher *et al*. (2005), Ya. Vytvytskyi (2008) and I.M. Petrenko *et al*. (2021), which confirms this opinion. Government support for preferential taxation of oil production from fields at a late stage of development is also important here, as it has been introduced, for example, in the United States and Canada. Thus, as noted earlier, these studies did not take into account or only partially take into account ways to solve the problem of increasing oil production at the later stages of field development. Not all of them consider economic factors, in particular. In this study, a comprehensive systematisation of the features of late-stage oil field development was carried out, and appropriate recommendations were provided that will not only temporarily increase productivity but also provide long-term benefits.

## Conclusions

One of the most important tasks was to determine the criteria for identifying the presence and structure of residual undeveloped oil reserves in the reservoir pore space. The main problems of the late stage of field development are summarised. In this aspect, the factors that cause low oil recovery factors were considered, including the difficulty of recovering residual reserves due to the low water displacement capacity, the actual filtration and capacitive heterogeneity of the pore space structure, and the low water displacement capacity in the reservoir pressure maintenance system, clogging of the pore space with mechanical particles and asphalt-paraffin deposits with the formation of low-permeability layers, and a package of unique and targeted methods of impacting the reservoir system (flow-diverting technologies, levelling of the injection profile, compaction drilling, isolation of aquifers and intensification of oil-saturated ones). The features of the late stage of oil field development were categorised into geological, technological, economic, social and environmental. Typical directions of technical and economic measures to stabilise and increase oil and gas production at the late stage of field development were formulated. Using the graph-analytical method, the authors proposed to determine the beginning of the late stage of field development based on the analysis of curves of accumulated oil production and water cut, which gives grounds for starting active investment in technical and technological processes of oil production. The "old" oil producing regions have significant potential for increasing recoverable reserves, both through additional exploration and improvement of field development systems.

This paper is a comprehensive study that not only analysed current issues and formulated the defining features of the late stage of oil field development, but also provided recommendations for further theoretical and applied research in the field of oil and gas production aimed at improving the supply of hydrocarbons to Ukraine and increasing the efficiency and profitability of hydrocarbon production. A thorough review and comprehensive grouping of the main factors was carried out and their architecture was built to select and justify effective measures to recover residual oil reserves, maintain production profitability and ensure environmental sustainability. The directions for further theoretical and applied research are: improvement and development of new methods and technologies for impacting the formation and bottomhole zone, optimisation of waterflooding systems to recover undrained residual reserves and increase oil production at the late stage of field development.

## Acknowledgements

None.

## Conflict of Interest

None.

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# Особливості розробки нафтових родовищ України на пізній стадії та напрямки нарощування видобутку нафти

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**Анотація.** Актуальність роботи полягає в ідентифікації типових стадій розробки нафтових родовищ та визначенні початку настання періоду пізньої стадії на підставі фактичних значень річного та накопиченого видобутку нафти й обводненості продукції свердловин. Метою роботи було визначення головних ознак пізньої стадії розробки та напрацювання техніко-економічних напрямків і заходів щодо стабілізації та нарощування видобутку нафти й газу. Здійснено аналіз можливостей нарощування власного видобутку нафти в Україні з використання ресурсного потенціалу родовищ, запаси яких відносяться до категорії важковидобувних. Сформульовано критерії, за якими окремі поклади й родовища містять важковидобувні запаси, та встановлено структуру таких запасів з урахуванням елементів залишкової нафтонасиченості порового простору. Установлено особливості розробки родовищ на пізній стадії у частині динаміки зміни показників розробки. Розглянуто геолого-промислові, економічні, соціальні та екологічні проблеми, що супроводжують розробку родовищ на пізній стадії. На прикладі розвитку нафтовидобувної галузі України виконано аналіз типових стадій освоєння родовищ та видобування нафти й газу. Представлено структуру запасів нафти, класифікованих на активні, що вилучаються здебільшого за рахунок природної пластової енергії, та важковидобувні, які вимагають застосування спрямованої штучної дії на пластову систему з використанням різноманітних адресних методів і технологій. Запропоновано й показано на реальних фактичних даних процедуру визначення початку пізньої стадії розробки родовищ за кривими фактичного накопиченого видобутку нафти та обводненості продукції свердловин. Ідентифіковано локацію залишкових важковидобувних запасів у нафтонасиченому поровому просторі. За наявною середньо-статистичною інформацією всебічно розкрито визначальні ознаки пізньої стадії розробки, які угруповано на геологічні, технологічні, організаційні, економічні, фінансові, соціальні та екологічні. Визначено головні напрямки дії науково-дослідних і нафтогазовидобувних компаній на вирішення проблеми стабілізації та нарощування видобутку нафти на пізніх стадіях розробки родовищ

**Ключові слова:** нафтові родовища; показники розробки; важковидобувні запаси; залишкова нафта; нафтовилучення; збільшення видобутку