CHEMISTRY & CHEMICAL TECHNOLOGY

Chem. Chem. Technol., 2024,
Vol. 18, No. 2, pp. 258–269

Chemical Technology

ADVANCED RESEARCH ON THE PRODUCTION, TRANSPORTATION AND PROCESSING OF HIGH WAXY OIL. A REVIEW

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https://doi.org/10.23939/chcht18.02.258

Abstract. Global demand for crude oil has grown significantly over the past two decades. However, conventional light crude oil production is declining, and more and more deposits of heavy and waxy oil, including high waxy ones, are being developed, creating new technological challenges at every level of the process, from production to transportation and refining. Among the various problems, the main one is wax deposition. Since the costs of maintenance, repair, and achieving the required low-temperature properties of commercial oil products are very high, solving this problem becomes critical. The paper discusses the existing problems of production, transportation, and refining of waxy crude oil and analyzes the methods of their solution.

Keywords: wax; deposits;, oil; flow assurance; rheological properties; WAT.

1. Introduction

Economic development and population growth in recent decades have led to an increase in demand for fossil fuels. This has led to a decline in so-called "conventional" oil reserves, which are insufficient to meet the ever-growing demand for fuel and energy. Unconventional oil reserves, which include heavy high-viscosity oil, ultra-heavy oil, oil shale, oil sands, tar sands, and bitumen, are an alternative to fossil fuels[1]. Taking into account the chemical composition and physico-chemical properties of unconventional oils, there are several serious problems associated with their production, transportation to refineries, and further ways of their rational processing[2,3].

Traditional waxy crude oil is a fairly common type[4]. Some waxy crude oils produced worldwide contain up to 32.5 % wax[5] and may be referred to as high waxy ones (high-paraffin oils). As a result of changes in the environment (temperature, pressure, velocity, *etc.*), the wax crystallizes and deposits. Wax deposits are one of the chronic problems of the oil industry and cause an increase in oil viscosity and higher values of its pour point. An increase in these values leads to a drop in system pressure, gel formation, reduced fluidity, and higher oil pumping costs[5].

According to different literary sources, waxy crude oil accounts for 20 %[6–9] to 30 %[10,11] of world production. Waxy Crude Oil Market Report[12] states that the global waxy crude oil market size is estimated at US$ 833.4 million in 2022 and is projected to reach an adjusted size of US$ 1,110.4 million by 2028 at a compound annual growth rate (CAGR) of 4.9 %.

According to the national classification, three types of oils (P1, P2, and P3) are distinguished depending on the wax content[13]. Type P1 includes low waxy oils with a wax content of no more than 1.5 wt. % with a melting point of 50 °C. This type is usually used to produce jet fuel without dewaxing, winter diesel fuel (fraction 240–350 °C) with a pour point not exceeding minus 45 °C and base oils with a pour point in the range of minus 10–30 °C, depending on their viscosity. Type P2 includes waxy oils containing from 1.51 to 6.0 wt. % of wax, provided that they can be used to produce jet fuel and summer diesel fuel (fraction 240–350 °C) with a pour point not exceeding minus 10 °C without dewaxing, and distillate oils with dewaxing. High waxy oils with more than 6.0 wt. % of wax are classified as P3. Without dewaxing even summer diesel fuel cannot be produced from them. It is recommended to use these oils for wax production. A significant part of crude oils produced in Ukraine are waxy and high waxy ones[14].

In general, waxy crude oils contain mainly n-paraffins and small amounts of branched and cyclic paraffins. However, some crudes contain *n*-paraffins in small quantities relative to branched and cyclic paraffins[15]. The latter ones have a high pour point, which causes a deterioration in the rheological (mobility, fluidity, *etc.*) and low-temperature properties of both the oil itself and

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the oil products obtained from it. This fact harms the process of oil production, transportation, and refining. Therefore, it is an object for research to improve the technological efficiency of the oil industry. In addition to waxes, oils also contain resins and asphaltenes, which are non-hydrocarbon components of oil. Their content in oil can vary from 2–5 to 20 % or more[16].

It is possible to prevent wax crystallization by oil heating to 50–60 °C, but this method sometimes leads to unnecessary costs and is economically unjustified. In some cases, this procedure is not possible at all. Reducing the crystallization temperature can be achieved by mixing high waxy oil with low waxy oil or with solvents, which also leads to additional time and resources.

The most effective way to improve the low-temperature properties of crude oils and refined products is to use depressants. These substances even in small doses (usually 0.05–0.10 wt. %) can significantly reduce the pour point and improve fluidity at low temperatures. Depressants are the most effective at temperatures below the level at which oil congelation occurs. This level is the highest cloud point of oil (the wax appearance temperature). Depressants do not dissolve wax and do not reduce its concentration; their action is aimed at changing the size, shape, and structure of particles in the dispersed phase. The additives modify crystals and prevent the growth of wax matrices, which are the main cause of oil congelation.

Thus, different approaches are used to prevent or eliminate wax deposits. However, research to develop more efficient methods is ongoing. The purpose of this paper is to systematically review and analyze publications on the problems that exist in the production, transportation, and refining of high waxy oils, as well as existing methods for solving them, their advantages and disadvantages.

2. Relation between Wax Content and Oil Properties

The presence of wax is primarily responsible for the low-temperature and rheological properties of crude oil. Petroleum wax (Fig. 1) is a complex mixture of high molecular weight alkanes consisting of straight, branched, and cyclic chains in a solid or liquid state at room temperature[17,18]. Wax refers to a mixture of *n*-alkanes and *iso*-alkanes with a carbon number in the range of C20 to C60[4]. It precipitates out of crude oil when the temperature is below the wax appearance temperature (WAT)[19], and this precipitation can cause an increase in viscosity and a decrease in fluidity during the transportation process. The wax appearance temperature, also known as the cloud point[20], is an important characteristic for assessing the potential deposition of wax from oil.

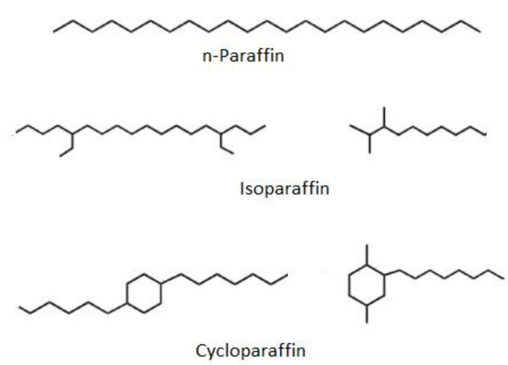


Fig. 1. Composition of petroleum wax

Before deposition occurs, wax first crystallizes or precipitates from the crude oil. Wax precipitation occurs in two stages known as nucleation and crystal growth[21]. Nucleation occurs when the temperature of the crude oil reduces to the WAT. The wax molecules form clusters, which causes turbidity, which is expressed by the term "cloud point" and correlates with the WAT value. Gradually, wax molecules join and detach until they reach a cluster of a critical size to be stable. These clusters are better known as nuclei, and the formation of these nuclei is defined as nucleation. Homogeneous nucleation of crystallization centers occurs in the absence of contaminating or nucleating materials. Meanwhile, heterogeneous nucleation occurs in the presence of nucleating material(s) throughout the liquid. The process of crystal growth begins after the nuclei have stabilized, as molecules subsequently attach to the lamellar structure[17].

Researchers usually divide the wax, which is presented in petroleum crudes, into two groups[22]: solid or macrocrystalline wax (Fig. 2, *a*) and microcrystalline wax (Fig. 2, *b*). The wax of the first group has a straight carbon chain with a length of C16 to C40 (*n*-alkanes) and crystallizes in the form of plates or needles, while the second group has a high percentage of *iso*-paraffin hydrocarbons and naphthenic rings with a carbon chain of C30 to C60 and crystallizes in an amorphous structure[23,24]. Microcrystalline wax is usually present in petroleum distillates and residues.

The reasons for the high molecular weight or the presence of wax with a higher carbon number are still under investigation. One possible explanation is that waxes with a higher number of carbon atoms are composed of molecules with a lower number of carbon atoms that are formed in reactions at lower temperatures. For example, C50 wax consists of two C25 ones, and C70 consists of two C35 ones[25].

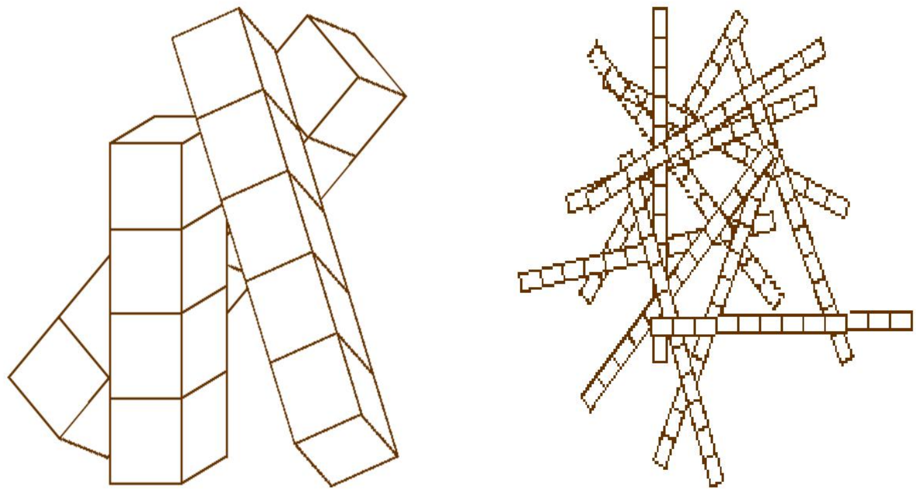


Fig. 2. Macrocrystalline (a) and microcrystalline (b) wax[22]

Recognized as the main components of the macrocrystalline line, *n*-paraffins form well-defined needle-like crystals. Branched-chain paraffins make up the bulk of microcrystalline waxes. Long, straight-chain naphthenic and aromatic alkanes also contribute to the formation of microcrystalline waxes and have a significant impact on the type of crystal growth. Macrocrystalline waxes lead to wax problems in production and transportation; microcrystalline waxes contribute the most to bottom sediments in tanks. Misra *et al.*[26] note that waxes deposited during crude oil production and transportation are predominantly composed of *n*-paraffins with small amounts of branched and cyclic paraffins and aromatic hydrocarbons.

Garcia and Urbina[27] demonstrated that high molecular weight linear paraffins are responsible for the wax deposition in crude oil. A quantitative correlation was established between the molecular weight distribution and the experimentally determined flow properties of crude oil. The authors note that the wider the molecular weight distribution, the lower the risk of wax crystallization.

The relationship between wax content and crude oil properties has been studied in many works[4,19,20,23,25,27–30]. Numerous factors can affect viscosity changes in oil and oil/water emulsions, *e. g.* wax crystallization[28], nano-particle aggregation[29,30], *etc*. However, the knowledge about the mechanisms at the molecular level that lead to the changes in the WAT and viscosity is limited[4]. Thus, understanding of wax deposition mechanism has attracted the attention of researchers, including the application of molecular dynamics simulations, which have been used to study hydrocarbons and organic molecules[31]. Most crude oil simulations deal with asphaltene crude oil, focusing either on the behavior of the polar components of the oil or on the interaction between oil and water. However, a very limited number of simulations focus on waxy crude oil, as well as the behavior and role of wax molecules in the crude oil.

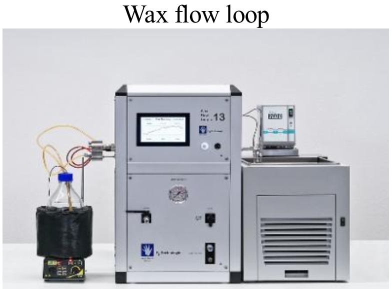
Yang *et al.*[32] provide consistent experimental evidence to demonstrate that molecular diffusion alone is not sufficient to describe wax deposition. They propose to consider non-Newtonian features of waxic crude oils when describing wax deposition using molecular diffusion.

Consequently, research in this area is actively ongoing. Although molecular diffusion was commonly accepted in all models as the main deposition mechanism, the contribution of shear forces to the accuracy of wax deposition models cannot be overestimated. In general, further research on wax prediction models should focus on complex media such as multiphase flow, turbulent flow, *etc*., and on validating the models with field data due to the significant discrepancies between models and field data.

3. Testing Methods

In the analysis of waxy oil, as well as in the testing, development, and selection of wax inhibitors, it is important to perform tests quickly, efficiently, and under reproducible conditions. A summary of the main methods is provided in Table 1.

Table 1. Testing methods for waxy oil and wax inhibitors

Method	Assignment	Principle	Remarks
Pour Point Test 	Flow assurance and inhibitor testing	During this relatively simple test, the temperature is slowly reduced and it is noted at what point the fluid becomes too viscous to flow	The test helps to define the lowest operating temperature for crude oil and thereby helps to monitor the proper fluidity of oil
WAT 	Flow assurance and inhibitor testing	The Wax Appearance Temperature (WAT) is usually the first parameter to consider when assessing whether wax contained in crude oil can become an issue during production. It is defined as the temperature at which first wax crystals start to form on cooling	The test can be used for research on flow improvers
Cold finger 	Flow assurance, wax deposition and inhibitor testing	The Cold Finger is an inverted pipeline. A cooled metal finger simulates the inner wall of the pipeline. Heated and mixed oil flows around it. When the temperature of the finger drops below WAT, wax begins to deposit on its surface	The test can be used for research on wax inhibitors
Wax flow loop 	Flow assurance, wax deposition and inhibitor testing	Method allows to predict the onset and amount of deposition depending on various factors, such as flow velocity (shear), temperature, and pressure	Test for deposition simulation of complex and heavy organic compounds in reservoirs, well heads, and pipelines
Pipeline restart loop 	Yield strength testing	The pipeline is filled with the sample and cooled to the set temperature. After cooling, the pump pushes the sample through the pipeline at a very low flow rate. The pressure vs. time curve shows the maximum yield strength	This test provides the ability to develop and test wax inhibitors under reproducible conditions

Note: All photos are taken from F5 Technologie advertising site https://www.f5-tech.de/

4. Problems Associated with High Waxy Crude Oil

4.1. Problems of Wax Crystallization and Deposition in Oilfields

Wax deposits in oil fields primarily lead to a decrease in oil production. Solid waxes are deposited in oil wells along the entire path of oil movement as temperature and pressure decrease. This releases gas from the oil, cools the flow, and reduces the solubility of the oil. Wax is deposited most intensively in the lifting pipes. In the process of extracting high waxy oil, wax precipitation is inevitable, as the temperature is always decreasing. Under these conditions, in addition to waxes, oily asphaltenes and resins are also released[16].

In the production of waxy crude oils, when considering the problem of solid deposits formation, which leads to complications in the operation of wells, oilfield equipment, and pipeline communications, it is necessary to consider not only waxes but also asphaltene-resinous deposits, the so-called asphalt-resin-wax deposits (ARWD). As a result, the living cross-section of the elevator column decreases, which leads to a decrease in its throughput, a decrease in the current flow rate of wells, and a decrease in their productivity[33]. A typical analysis of oil well equipment deposits shows that waxes are the dominant type (52 %), and the percentage of asphaltene-resinous substances is about 5 % (the balance consists of crude oil, water, and mechanical impurities)[26].

Oil production practice at oilfields shows that the main areas of ARWD accumulation are well pumps, well casing, well plumes, and tanks of industrial collection points. The most intensive accumulation of ARWD occurs on the inner surface of the well lift pipes[33]. In the discharge lines, their formation intensifies in winter, when the air temperature is much lower than the temperature of the gas and oil flow.

Crude oil can form wax as soon as it enters the well. Wax deposits and solidifies in formation pores and fluid channels, in the wellbore, on the sidewalls of wells, in tubing, perforations of the casing, pumping strings and rods, and throughout the oil transportation system in lines and pipelines[34]. It is the effect of wax formation in crude oil that often leads to pipe plugging, which causes frequent and expensive repairs.

Timely and well-planned removal of wax deposits is essential to maintain normal operations. Wax accumulation in wells can cause many of the above problems, as well as rod breakage due to overloading and sticking of service tools inside the well[35].

For many years, engineers and researchers have been proposing various methods to prevent wax deposition. El-Dalatony *et al.*[36] critically examine the status of existing and prospective research on wax deposition in operating crude oil wells and pipelines and methods of its elimination during oil production. In general, all methods are divided into thermal, mechanical, and chemical[35].

Wax deposition is highly temperature dependent, so ***thermal methods*** can be highly effective in both preventing and eliminating wax deposition problems. Good results are achieved by injecting hot oil, which is heated to a temperature above the wax melting point and then injected into the well. The circulating hot oil melts and dissolves the wax, allowing it to come to the surface. High molecular weight waxes are typically deposited at the high-temperature end of the well, while low molecular weight fractions are deposited as the temperature decreases up the wellbore[37]. The disadvantage of this method is its time consumption which slows down production.

Thermochemical treatment is one of the most promising methods that can be used for thermal stimulation of production wells to mitigate formation damage and increase hydrocarbon production[38]. Using special thermochemical fluids, high temperatures, and pressures can be created in the well. Several authors[39,40] have reported the use of thermochemical fluids, such as magnesium sulfate, ammonium chloride, and sodium nitrate solutions, to generate heat and pressure in the conditions of the well.

Mechanical removal of wax deposits involves the use of rod scrapers, wire scrapers, casing scrapers, free-floating piston scrapers (in gas lift wells), and casing scrapers to remove wax deposits from production tubing and pipelines[18]. Mechanical removal is a typical preventive strategy[41] to avoid complete clogging, although it is not always effective. Most of the costs of this technology are associated with the downtime required for operations. Even if the technology is inexpensive, it sometimes requires some additional solutions, such as looping flows or creating start-up and receiving conditions[42]. High-frequency treatment can cost tens of millions of dollars, which is significantly more expensive than competing solutions such as wellbore wall insulation or chemical flow improvers[10].

Waxs are chemically stable. For this reason, many types of high waxy oils are processed with the addition of ***chemical modifiers*** of their rheological properties. The fluidity of high waxy oils is affected by the number and shape of the formed wax crystals. The process of modifying the rheological properties of high waxy oils involves the addition of certain reagents that allow changing the morphology of wax crystals. The addition of such substances is most effective at pressures and temperatures at which wax crystallization has not yet occurred. Jovanović *et al.*[43] have developed an additive called a melting depressant, which is used to reduce the melting point and shear stress. In crude oil, the total wax content and wax distribution vary significantly. Therefore, the most effective melting point depressant has been invented and developed separately for each type of oil.

Other types of additives include wax inhibitors[44], pour point depressants[45], wax removers, and flow improvers[33].

Wijayanto *et al.*[46] confirmed the effect of aluminosilicate injection on improving wax oil recovery. Their experimental results showed that aluminosilicate nanoparticles can change the wettability of the rock surface from water-wetted to more highly wetted and reduce the interfacial tension between the oil and the injection fluid.

One of the most recent innovations in the remediation of wax deposits is the use of nanocomposite pour point depressants (NPPD)[47,48]. It is reported that these depressants change the morphology of wax crystals, which causes a decrease in the yield strength of wax deposits. It is also noted that the effectiveness of pour point depressants is significantly enhanced when magnetic fields of optimal frequency and intensity are applied to the deposits[49].

The use of modifiers of rheological properties is important in solving the fluidity problem of high waxy oils[43]. This method solves the problem of flow in tubing, well pipelines, process tanks, and oil pipelines.

4.2. Problems of Flow Assurance

Crude oil transportation lines play an important role in ensuring a continuous supply of fuel, *i. e.*, flow assurance. Since the maintenance costs of repairing and troubleshooting transportation lines are very high, solving problems related to flow assurance becomes critical in the oil industry[50].

The transportation of high waxy crude oil through pipelines can cause numerous problems that have an economic and technical impact on pipeline operations. The severity of the problems associated with waxy crude oil largely depends on the complexity of its rheological properties, which in turn depend on the operating conditions (mainly temperature).

Wax molecules appear as a liquid phase in crude oil in the Newtonian fluid region at reservoir temperature and pressure; in this case, the viscosity of the fluid is independent of temperature. When the wax is cold, its molecules crystallize and become solid[51]. The wax deposition in pipelines at the cloud point or the WAT and below basically leads to a sharp decrease in solubility, and the wax molecules solidify and become a gel, reducing the cross-sectional area of the pipelines[52]. The resulting gel is a consequence of the complete phase change of the waxy crude oil, which impedes flow, causes significant non-Newtonian behavior[53] and increases the effective viscosity as the temperature of the waxy crude oil approaches the pour point[11,54], and ultimately reduces the transportation efficiency.

As mentioned above, the wax particles in crude oil are initially in a dissolved form and crystallize when the pipe wall temperature drops below a certain temperature. The wax then precipitates, crystallizes, and accumulates on the pipe walls. This process is explained by the molecular diffusion of wax particles to the pipe wall when the temperature of the crude oil drops below the WAT.

The issue of wax accumulation is complicated because many factors affect wax deposition, such as its concentration in the crude oil, ambient temperature, the WAT, pressure drop, oil viscosity, and temperature. The main problems associated with wax deposits in crude oil transportation lines are flow assurance and sudden plugging, which can lead to immediate maintenance and repair. The deposited layer of wax in transportation lines can be observed as three sublayers: the top layer is more granular and softer, the bottom layer has a strong bond with the pipe wall and is considered a tightly adherent layer, and the intermediate layer contains mechanical impurities and high content of wax. Over time, the layers harden and move from the top to the bottom, thus reducing the effective cross-section of the flow[50].

The transportation of waxy crude oil faces major challenges not only because of its temperature dependence but also because of its shear dependence. At high temperatures, waxy crude oil exhibits low viscosity Newtonian behavior, where the resistance to flow due to friction is low, and thus low pumping pressures are required for transportation. However, at low temperatures, crude oil exhibits non-Newtonian behavior, where its viscosity becomes shear-dependent[53]. In such a case, the operated pipeline must maintain high pressure to guarantee continuous flow. In addition, due to heat exchange between the internal pipeline and the environment, the oil temperature decreases along the pipeline. As a result, the viscosity of the crude and therefore the friction resistance increases. If the flow is interrupted for any reason, such as an emergency or planned shutdown, the ability to restart the pipeline becomes a problem due to the lack of heating generated by friction.

It was shown by Mohyaldinn and co-workers[55] that during the operation of a pipeline of wax crude oil, the temperature decreases along the axial length due to heat transfer caused by the temperature difference between the transported crude oil and the environment. This decrease in temperature occurs simultaneously with an increase in temperature caused by heat generation due to friction, which is proportionally related to velocity gradients. This change in temperature along the pipeline causes an axial change in rheological properties, which leads to a change in frictional pressure loss. The authors present the rheological properties of waxy crude oil; they explain and describe how these properties can affect the pressure loss inside the pipeline during operation and shutdown. They also discuss the measures that must be taken into account when designing a pipeline.

The correlation between crude oil properties and rheology, including wax deposition and wax accumulation during flow, and methods for its elimination, have been extensively studied by many researchers[6,8,9,11,17,34,50–72]. In general, most of the works related to the problems of high waxy oil are focused on the study of crystallization and deposition of wax in pipelines, rather than in oil wells or at technological units. This is due to the simplicity of theoretical formulation, laboratory testing, and real monitoring of wax deposition in more accessible pipelines[41].

The principles underlying thermal, mechanical, chemical, and biological methods of inhibiting and removing wax deposits are described in detail by several authors[50,59,72]. The number of scientific papers devoted to the problems of flow assurance and published for the period from 2000 to 2020 yrs. is presented in Table 2. This analysis was conducted to demonstrate the growing interest of the scientific community in the above-mentioned commercially used methods. As can be seen from Table 2, there is a gradual increase in research on the development of all methods of wax deposition. The leader of publications is the chemical method.

Table 2. The number of published scientific papers on the problems of flow assurance of high waxy oil

Method	Years of publication				
	2000	2005	2010	2015	2020
Thermal	25	25	49	83	123
Mechanical	10	12	28	58	101
Chemical	24	30	50	94	148
Biological	8	10	25	40	63

Thermal methods are mainly used to maintain the temperature of the environment or to maintain the temperature of the crude oil to reduce the accumulation of wax. By maintaining the fluid at a temperature above the cloud point of the crude oil, effective thermal insulation can prevent wax deposition. Although linear heaters can be effectively used from the wellhead to other facilities, the physical characteristics of the crystallized waxes are not changed in any way[61]. Wax deposition can be prevented by using an insulating agent that also serves as a coating. Since the goal of thermal insulation is to limit the movement of heat from the inside to the outside, low thermal conductivity is a prerequisite for any material used in the process. A variety of organic and inorganic materials can be used to insulate a pipeline design from heat. However, the best materials in this situation are plastics.

Pylypiv[73,74] analyzed the effectiveness of heat treatment of high waxy Dolyna oil (Ukraine) on its transportable properties[73] and hydraulic losses in the oil trunk pipeline[74]. It was experimentally established that the proposed heat treatment technology (heating to 60 °C and cooling at a rate of 20 °C/h) significantly improves the rheological and transportable properties of high waxy oil and, as a result, makes it possible to reduce energy costs for oil pumping within the operating temperature range.

Among ***mechanical methods***, magnetic fluid conditioning (MFC) technology is of interest. This method helps to avoid the accumulation of wax deposits and wax agglomeration by polarizing the wax molecules in the direction of flow. The agglomeration of wax crystals is disrupted by a magnetic field, which changes the kinetics of the deposited wax and makes it difficult for the wax to deposit and develop larger crystals. According to Elkatory *et al.*[59], the method does not affect the WAT, but it increases the viscosity of crude oil. However, there is little evidence of the effectiveness and success rate of the method.

Among the mechanical and chemical methods, the industry prefers the latter. ***Chemical methods*** mainly consist of the addition of chemical inhibitors to the oil to reduce the wax deposition. Essentially, wax crystals are formed through nucleation, growth, and agglomeration processes, while the precipitation of these waxes occurs through molecular diffusion and shear dispersion. Inhibitors can control the growth of wax crystals through nucleation, co-crystallization, adsorption, and dispersion interaction[9].

Chemical wax inhibitors are usually divided into four main groups, including solvents, crystal modifiers, dispersants, and surfactants[17,68]. Surfactants and dispersants are surface activators that keep the wax particles suspended and dispersed, reducing the adhesion of the particles to each other, to the pipe walls, or to any hard surface. Other types of surfactants modify solubility by solubilizing the core and preventing agglomeration of the wax particles. Some authors[63,64,75] refer to wax crystal modifiers as pour point depressants. Modifiers inhibit the growth of wax crystals because they reduce the ability of wax crystals to form three-dimensional structures[50,70]. As a result, the viscosity, yield strength, and pour point of waxy gels decrease, hence the name − pour point depressant (PPD)[71].

Makwashi *et al.*[23] describe a simple method for optimizing inhibition by mixing four polymer-based pour point depressants. It was shown that the depressants cause morphological changes in wax crystals, turning needle-like crystals into agglomerates. Small particles dispersed in the oil matrix reduce the viscosity and gelling properties of wax. The improvement can be attributed to the interaction between the wax inhibitor molecules and the wax crystals. Mixing different depressants creates a synergistic effect that effectively reduces viscosity, the wax appearance temperature, and the pour point of waxy oil.

Among the latest methods, it is worth noting the use of nanotechnology, which has become a potential solution for optimizing traditional wax removal and/or inhibition processes due to its exceptional effectiveness in changing the morphology of wax and co-crystallization behavior[8]. The effect of two commercial wax inhibitors on wax formation and crystallization was studied by adding SiO_2 nanoparticles. As a result of this effect, the thickness of wax deposits in the pipeline decreased by more than 5 %.

Ridzuan *et al.*[66] studied the behavior of a commercial depressant in the absence and presence of a clay-based nanomaterial on wax deposition, showing that nanoparticles can change the solubility of wax crystals in crude oil. According to the authors, the addition of nanoparticles to depressants improves the inhibition efficiency by 11 % compared to using a depressant in the absence of nanoparticles.

The results confirming the positive effect of adding nanoparticles to wax depressants were also presented by Vakili *et al.*[65], Wang *et al.*[67], VijayaKumar *et al.*[69].

Polymeric chemical additives are also used to reduce the pour point, viscosity, and yield strength of waxy crude oil. Polymers prevent the aggregation or precipitation of wax-forming particles by creating inter-particle barriers (*i. e.*, changing the crystallinity of the wax), which ensures a continuous flow of waxy oil. However, such chemicals are often limited by their compatibility, cost, and environmental or human health implications. In case of extreme temperature drops, a large dose of these chemicals may be required[62].

Alade *et al.*[62] focus on the study of ensuring the flow of waxy crude oil using an environmentally safe and cost-effective approach involving a thermochemical reaction. Experimental results confirm that a thermochemical fluid can significantly increase the temperature of high waxy crude oil above the pour point. It was also noted that more than 95 % of the deposited wax can be removed from the contaminated pipe without visible damage to the pipe material. Furthermore, using thermochemical fluid to waxy crude oil ratios ranging from 14 to 33 % (v/v), the simulation results show a significant improvement in flow conditions in terms of flow temperature, flow pressure, total pressure drop, and most importantly, a reduction in wax deposition of up to 98 %.

The innovative microbial method of wax treatment is not widespread but was found to be effective in several field tests[50]. Under the influence of bacterial culture, a biosurfactant is formed, which is a wax inhibitor. It has also been observed that bacterial treatment reduces the WAT of crude oil. This makes it less susceptible to wax deposition[60].

Gabayan *et al.*[34] present a comprehensive review of the potential of bio-derived alternatives as flow improvers for waxy crude oil. The review emphasizes the promising results of bio-derived alternatives rich in unsaturated fatty acids in reducing the agglomeration and deposition of wax molecules in crude oil. The polar esters of seed oils alter the surface of wax resulting in the formation of a solvated layer that reduces the co-crystallization of non-polar esters, thereby reducing the formation of wax aggregates. The study also suggests that the rheological properties of the oil can be optimized by esterification with alcohols with lower pour points and viscosities, which may increase the ability of these alternatives to improve the fluidity of crude oil.

Biological alternatives can address flow assurance challenges in the petroleum sector by reducing reliance on traditional pour point depressants. The addition of natural cashew nut shell oil, extracted from biomass waste, has been shown to decrease the pour point of oil and modify the morphology and microstructure of wax crystals. As a result, the flow properties of waxy oil were improved[76]. Cheap natural chemicals derived from jatropha seeds and castor oil decreased the pour point, as well as the viscosity of high waxy oil more effectively than the well-known triethanolamine[77].

The published experimental results confirm that bio-based flow improvers derived from cheap renewable resources are attractive as cost-effective, environmentally friendly alternatives to conventional applications.

Thus, taking into account conventional methods and the latest modern technologies, it can be concluded that research on the development of new chemical inhibitors, avant-garde devices, and effective bacterial treatments continues and remains relevant.

4.3. Problems of High Waxy Crude Oil Refining

According to Waxy Crude Oil Market Report[12], among the leading waxy crude oil industry companies are Saudi Aramco, National Iranian, CNPC, Kuwait Petroleum, ExxonMobil, BP, Petrobras, Pemex, ADNOC, Shell, Chevron, and Qatar Petroleum. These companies have extensive experience and infrastructure in oil exploration, production, and processing. The processing of high waxy crude oil, especially in the existing refineries, presents many difficulties due to its unfavorable characteristics.

Each refinery determines the type and volume of each crude input needed to maximize the profitability and efficiency of the refinery. The presence of wax, which is found mainly in the heavy fractions of high waxy crude oil, forces refiners to take special measures during the production of petroleum products to ensure that their low-temperature properties meet requirements and specifications. Obviously, specifications must be stricter when products are used in the cold season or cold climates.

Scientific research in this direction aims to increase efficiency and effectiveness in dealing with the unique challenges posed by waxy crude oil.

Tripathy *et al.*[78] investigated the possibility of treating crude oil in a refinery with a mixture of solvents such as MEK and nitrobenzene in the presence of ultrasonic waves. The authors investigated the thermodynamic changes in Indian crude oil samples after adding a mixture of solvents and sonication. The obtained results confirm that the use of sonication of a mixed organic solution can be a novel approach suitable for increasing the efficiency of wax extraction from crude oil.

Depressant applications are actively used to increase the throughput of transportation lines, reduce the downtime of railroad tank cars when draining oil and reduce the residues of the transportation product after unloading at refineries, reduce the cost of heating oil and cleaning operations to remove waxy deposits, for example, in tanks, to reduce pumping pressure[35]. Their use is quite widespread and generally leads to a reduction in the cost of petroleum products[10].

Both types of wax, macro- and microcrystalline, are commonly found in the oily fractions of crude oil and cause problems in the equipment of processing plants and flow problems in process lines[5].

Since the main problems in the processing of high waxy crude oil arise in the processing of oil fractions, a dewaxing process is used to remove wax from both distillates and residual base oils during the distillation processes. There are two types of dewaxing processes: selective hydrocracking and solvent dewaxing.

Catalytic dewaxing is a special hydrocracking process used to improve the cold flow properties of middle distillates and lubricants, namely the pour point and viscosity of middle distillates and lubricants, the cloud point of diesel fuel and the pour point of jet fuel. The one-step hydrocracking process can be used for catalytic dewaxing with or without hydrotreating, depending on the sulfur and nitrogen content in the feedstock. The catalytic process is carried out over a bifunctional zeolite catalyst in a hydrogen stream. A base metal (*e. g.*, nickel) deposited on a medium-porous zeolite, such as ZSM-5, can be used[79].

Solvent dewaxing is a more common method. Methyl ethyl ketone (MEK) is used as a selective solvent. The efficiency of dewaxing increases at higher mixing temperatures and lower cooling temperatures[25].

Among the modern dewaxing methods is the Texaco dewaxing process (also called the MEK process), which uses a mixture of MEK and toluene as a solvent, and sometimes mixtures of other ketones and aromatic solvents. The Exxon Dilchill dewaxing process uses direct cold dilution-cooling of the solvent in a special crystallizer instead of the scraper surface heat exchangers used in the Texaco process. The Di/Me dewaxing process uses a mixture of dichloroethane and methylene dichloride as the dewaxing solvent. The propane dewaxing process is essentially the same as ketone dewaxing, except that propane is used as the dewaxing solvent, so high-pressure equipment is required, and cooling is carried out in evaporative coolers by evaporating some of the dewaxing solvents. Although this process yields a better product and does not require crystallizers, the temperature difference between the dewaxed oil and the filtration temperature is higher than in ketone processes (higher energy consumption), and additional dewaxing aids are required to obtain good filtration performance[80].

High viscosity and pour point of waxy crude oil and its gelation cause difficulties during refining processes. Wax deposit and waxy oil flow characteristics lead to column plugging, losses of hydrocarbons, and, in general, higher production costs.

5. Conclusions

A large number of papers have been devoted to the study of the problems in the production, transportation, and refining of waxy oil. Wax deposition, which leads to reservoir damage, flow restriction, and reduced productivity, is a critical operational issue in the oil industry. Wax problems cause billions of dollars in losses for the oil industry worldwide due to the cost of chemicals, production cuts, well closures, reduced throughput, pipeline plugging, and equipment failures. A deep understanding of such problems is of paramount importance for the oil industry to find new technical and economic solutions.

This review discusses the main problems caused by wax deposits, as well as methods for preventing and removing these deposits from waxy crude oil. It describes the main methods, such as thermal, chemical, mechanical, and biological methods, as well as promising non-chemical and environmentally friendly technologies for controlling the wax deposition process.

The article provides interested researchers with a brief overview of research progress in this area and provides references for future work. It is noted that more research on wax deposition prediction models should focus on complex environments such as multiphase flow, turbulent flow, *etc*., and emphasize the need to validate models using field data. The importance of continuing research on the use of alternative additives that can contribute to the development of sustainable and environmentally friendly technologies in the oil sector is emphasized. In addition, it is necessary to conduct scientific research to assess the long-term impact of nanoparticles on human health and the environment, as well as to develop appropriate safety protocols and regulatory frameworks to mitigate any potential risks.

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Received: December 16, 2023 / Revised: January 25, 2024 / Accepted: February 01, 2024

СУЧАСНІ ДОСЛІДЖЕННЯ ВИДОБУТКУ, ТРАНСПОРТУВАННЯ І ПЕРЕРОБЛЕННЯ ВИСОКОПАРАФІНИСТИХ НАФТ. ОГЛЯД

Анотація. *Світовий попит на сиру нафту значно зріс за останні два десятиліття. Однак, видобуток звичайної легкої сирої нафти зменшується, і все більше розробляються поклади важкої нафти, включаючи високопарафінисті, що породжує нові технологічні проблеми на кожному рівні процесу, від видобутку до транспортування та перероблення. Серед різноманітних проблем основною є відкладення парафіну. Оскільки витрати на технічне обслуговування, ремонт і досягнення необхідних низькотемпературних властивостей товарних нафтопродуктів дуже високі, вирішення зазначеної проблеми стає критичним. У роботі розглянуто наявні проблеми видобутку, транспортування і перероблення високопарафінистих нафт, а також проаналізовано методи їхнього вирішення.*

Ключові слова: *парафін, відкладення, нафта, забезпечення потоку, реологічні властивості, температура початку кристалізації.*