

# A Review of Wax Mitigation Methods through Hydrocarbon Production

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## ABSTRACT

The world demand for energy has led oil companies to expand their operations in the cold environments such as the offshore deep-water for more reservoirs. During hydrocarbon production, oil companies are challenged with the problem of wax deposition from the crude oil building up on the pipe wall. The precipitated solid phase of wax, creating pressure abnormalities and causing an artificial blockage leading to a reduction or interruption in the production. It leads to increases in operational and remedial costs while suppressing oil production. This research outlines the important methods that used to reduce or mitigate wax deposition in the hydrocarbon production systems around the world, such as the chemical, mechanical, thermal methods, or a combination between them, microbial treatment, cold flow, cold-oil recirculation method, choke cooling method, the wax eater method, magnetic-fluid conditioning method, Eco-wave TM treatment, ultrasonic wave treatment, bacterial treatment, and spiral flow method. Many researchers have been used various different types of chemical inhibitors, such as polyethylene, ethylene/vinyl acetate copolymers, copolymer esters, polyacrylate polymer, ester/vinyl acetate copolymers, olefin/ester copolymers, polymethacrylates, alkyl phenol resins, xylene and toluene. The reduction in wax deposition was 100% after using the influence of bending spiral flow with polyacrylate polymer at a concentration of 1000 ppm and 2000 ppm at different time and flow rates, and the ambient temperature was 33°C. The reduction in wax deposition was 100% after using the effect of bending the spiral flow with the inhibitor at a concentration of 500 ppm at flow rate 4.8 L/min, and the reduction in wax deposition was 94% at the same concentration and flow rate 2.7 L/min. Despite of all the previous mitigation methods, many oil companies still suffer from wax deposition problems and are still looking for a good solution to solve this issue.

**Keywords:** Waxy crude oil; Wax deposition; Pipeline and facilities; Mitigation methods

## INTRODUCTION

Wax deposition is one of the main flow assurance problems faced by the oil industry, affecting numerous oil companies around the world. Wax deposition can result in the restriction of crude oil flow in the pipeline, creating pressure abnormalities and causing an artificial blockage leading to a reduction or interruption in the production (Figure 1). The main causes of wax deposition are environmental changes, including temperature, pressure, and loss of dissolved gases, which affecting solution equilibrium, therefore pressure abnormalities are formed due to evaporated the dissolved gases (light components of the oil) from the crude oil. This pressure abnormality which means principally overpressure or under pressure will affects production capacity, wellhead oil pressure dropped significantly and faults in the separation facilities. However, in an extreme case, this can cause a pipeline or production facility to be abandoned. The wax deposition also leads to formation damage near the wellbore, reduction in permeability, changes in the reservoir fluid composition and fluid rheology due to phase separation as wax solid precipitates.

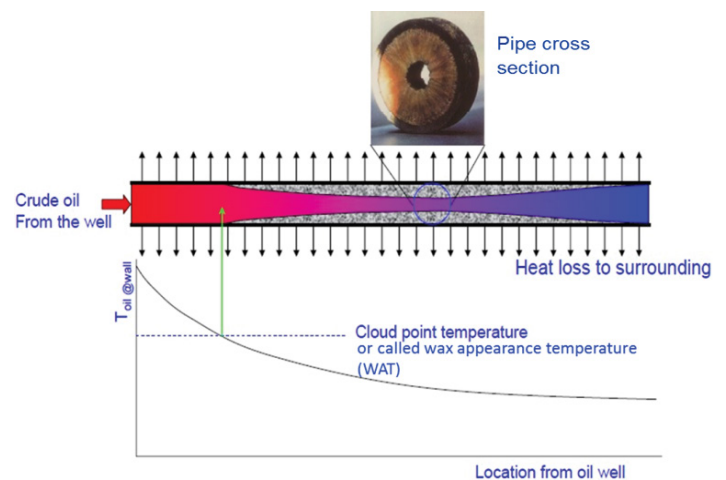


Figure 1: Wax deposition process in the hydrocarbon pipeline [1,2].

One of the important issues to be noted is that the wax deposit is not solid wax, but a gel that consists of solid wax crystals and trapped liquid. The deposit is also known to harden with time in a

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process termed aging. The precipitation of wax components out of the oil is responsible for changes in the waxy crude oil properties, including the gelation of oil and an increase in viscosity. Wax contains a high molecular weight n-Paraffin and consists of long chain alkanes with 20 to 50 carbon atoms. Wax can precipitate as a solid phase when the crude oil temperature drops below the wax appearance temperature WAT (the temperature at which the first wax crystals start to form in the crude oil in a cooling process) [1,2].

The main factor that affects the wax deposition process is the low temperature, which means that subsea pipelines are especially vulnerable. Therefore, wax deposition prevention becomes very important in deep-water oil production. Wax deposition in crude oil production systems can be reduced or prevented by one or combination of chemical, mechanical, and thermal remediation methods. However, with the advent of extremely deep production, offshore drilling and ocean floor completions, the use mechanical and thermal remediation methods becomes prohibitive economically, as a result, use of chemical additives as wax deposition inhibitors is becoming more prevalent.

The thermal methods include heat retention, active heating such as thermal insulations, bottom hole heaters, hot oil circulation and steam circulation. The mechanical removal method includes running scrappers in the borehole and pigging in pipelines at an intervention frequency.

The chemical inhibitors include pour point depressants (PPD), crystal modifiers, dispersants and solvents. Also, there are another mitigation methods such as, microbial treatment using microorganisms for wax mitigation, cold flow, cold-oil recirculation method, choke cooling method, the wax eater method, magnetic-fluid conditioning method, Eco-wave TM treatment, ultrasonic wave treatment, bacterial treatment, and spiral flow method.

Despite of all of those mitigation methods, many oil companies prefer chemical inhibitors in cold environments, considering this economic way and best solution to reduce wax deposition in pipelines due to chemical additives does not need to stop production for cleaning the pipe but it considers as an online mitigation method [1,2].

### Wax mitigation methods

This study lists a series of methods used to mitigate wax deposition in the hydrocarbon systems includes chemical, thermal, mechanical, a combination of methods includes mechanical-chemical treatment, and thermo-chemical treatment. Other treatments includes eco-wave TM treatment (Baker Hughes), Ultrasonic wave's treatment, bacterial treatment and spiral flow method.

### Mechanical removal methods

Mechanical-removal techniques are the oldest wax-removal techniques applied in the industry. The following are some established mechanical-removal techniques that used to remove wax deposits from flow lines, producing tubing and pipelines: rod scrapers, wireline scrapers, flow line scrapers, free-floating piston scrapers (in gas lift wells), pigging flow lines and wire lining tubing [2,3].

Use of pipeline-inspection gauges (PIGs) is a mechanical method that is the oldest and among the most widely used wax-removal techniques in the field, and has been reported previously [3-8].

PIGs have been used in the petroleum industry for more than a century, and there are arguments that suggest the acronym (PIG) may also have been derived from the squealing noise they make while traveling through a pipeline. A PIG is launched from a PIG launcher, which is a section of the pipeline with a larger diameter gradually reducing to the normal diameter of the pipeline. As the PIG is launched, the launching station is closed and the pressure-driven flow of the hydrocarbon in the pipeline pushes the PIG through to the receiving center. The PIG while traveling can scrape off the wax deposits from the pipeline walls. Figure 2 shows how a cleaning PIG can operate within a section of a subsea pipeline [2,3].

In order to perform mechanical clean-up by pig, a topside and subsea facilities for running pigs in well flowlines and oil pipelines must be installed. Frequency of the cutting or wire lining (for well treatments) and pigging (to remove depositions in flowlines) depends on the wax deposition rate in an individual well.

The improved flow due to the passing pig is probably caused by a combination of smoothing of the rough wax layer and removal of the wax back into the flowing well [3]. The pig selection depends on wax properties operating parameters. However, a maximum wax layer thickness of 2-3 mm is often used as pigging criterion [9].

Wax may be removed by scraping from the tubing wall while the well is still producing. Although such methods are economical, one major disadvantage is plugging of perforations within wells as a result of circulation of scraped paraffin through the well annulus. Another disadvantage is associated with wireline scrapers being stuck in wells during post-cleaning operations due to the deposit being too hard or the wax layer is too thick [3,10], expensive treatments, e.g. if wireline done more frequently costs will go up because special surface equipment and trained personnel required. Efficient utilization of pigging depends on proper wax deposition prediction. The scraping damages a well and decreases its productive life. Mechanical treatment may plug the perforations and increase the stability of oil-in-water emulsions [9].

On another hand, the advantages of the mechanical removals include good cleaning is assured, minimal formation damage [9]. Some of the advantages of using PIGs include low labor costs, simplicity of operation, and less downtime because cleaning may be faster compared with some of the other methods. However, retrieving a PIG that is stuck in a pipeline may be very expensive

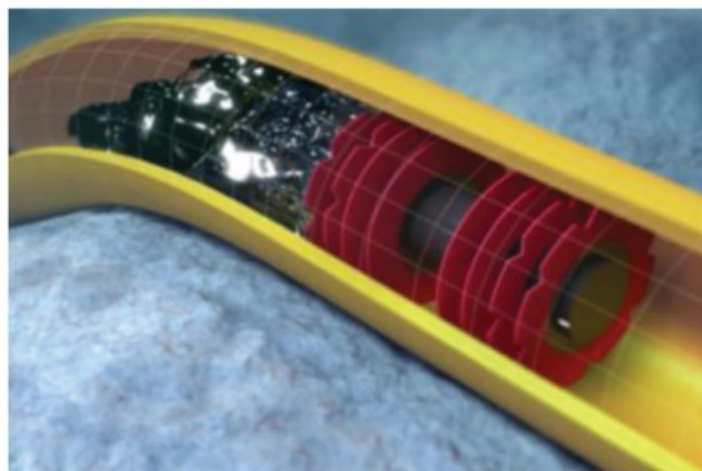


Figure 2: Pigging operation for wax removal.

[2,11]:

### Chemical inhibitors method

Chemical inhibitors are considered as the best solution for deep-water hydrocarbon production. The chemical inhibitors include pour point depressants (PPD), crystal modifiers, dispersants and solvents. Pour point depressants hinder the formation and growth of wax crystals by modifying the crystal structure (by merging with the edge of a growing wax crystal). Although this reduces the viscosity, yield stress and pour point of the oil, it cannot reduce the wax deposition rate [8,12,13].

Use of chemical inhibitors for wax mitigation in the field has been reported by several researchers [2,4,5,7,8]. Wax inhibitors are added to oils with high wax content to minimize problems associated with transporting oil. Wax inhibitors includes wax-crystal modifiers, detergents, and dispersants. The detergents and dispersants are surface-active agents that primarily keep wax crystals dispersed as separate particles and reduce their ability to interact and adhere to solid surfaces. These surface agents partly function by modifying the surface of the pipeline wall. One example is wetting the pipeline surface by water to prevent adhesion of paraffin. Some surfactants also solubilize the nucleus and prevent paraffin agglomeration [2,10].

The inhibition mechanism of the paraffin inhibitor is the prevention of wax incorporation into the deposit by weakening the deposit. Then shear forces in the flow can remove weaken wax deposit. It should be noted, that paraffin inhibitors do not provide 100% inhibition. Therefore, depending on inhibition levels, some additional method of remediating wax deposition may still be needed. These methods are usually pigging for flowlines and wireline cutting for wells. When used in conjunction with paraffin inhibitors, the frequency of pigging or wireline operations can be reduced. Also, the pigging and wireline cutting operations may potentially be performed easier since properly selected paraffin inhibitors produce weaker deposits. Hence, with paraffin inhibitor use, the danger of blocking a flowline with a stuck pig can potentially be decreased - both by reducing pigging frequencies and by making softer deposits.

For well with high bottom hole temperature chemicals are checked whether they can withstand this temperature; viscosity evaluation: for deep-water umbilical application system viscosity evaluation is performed at ambient temperature; compatibility with other chemicals (corrosion inhibitors, demulsifiers, etc).

Dispersant test is used to screen for tank bottom and interface control chemicals. Flask test used to screen for surface active detergent/dispersant combinations for batch treatment or continuous applications for downhole or flowline control. To select chemicals for deep-water umbilical application following specialized tests can be performed: capillary loop testing; high pressure viscosity measurements. Chemicals are most effectively applied as early in the production stream as possible. Bad logistics result in the improper addition of chemical under less than optimal condition, for instance, adding chemicals after the deposition "spot" may prevent deposition downstream, but the source of the problem goes untreated. So, chemical injection must be robust.

Advantages: chemicals may be the only method suitable for large offshore deep-water projects and is considered cost-effective;

chemicals have a potential for significant savings versus removal procedures.

Disadvantages: all wells cannot be treated the same. Each well is individual. Successful application of inhibitors somewhere else does not mean it will work well every time, trials have to be conducted on each well; Operating expenditure (OPEX) associated with chemical injection can be significant; (e.g. in pumping wells the production of any gas make it impossible to get chemical to the bottom of a well without a flash system or capillary); Environmental regulations and downstream requirements can limit the types and volumes of chemicals; No chemical solution can be available.

### Wax crystal modifier

Wax-crystal modifiers have structures similar to precipitating wax crystals. They co-precipitate with wax and compete with wax crystals by occupying their positions on the crystal lattice through hydrocarbon chains. Alternatively, they also create hindrances toward the growth of wax crystals. Wax-crystal modifiers are also known as pour-point depressants. The pour point is the minimum temperature at which oil flows freely under its own weight and specified test conditions. The pour-point depressants can alter the growth and surface characteristics of wax crystals. With pour-point depressants, wax crystals have reduced the tendency of forming 3D structures and sticking to metal surfaces such as pipeline walls.

These polymers interfere with the crystal growth and agglomeration processes, and therefore inhibit the deposition of paraffin (Figure 3). In addition to paraffin inhibition they also have a tendency to change the rheological properties of the oil by reducing the pour point, viscosity and yield value of the crude. Therefore modifiers are added ahead of fracturing. Deliverability of the polymer under varied temperature restrictions is the major problem. Crystal Modifiers selection methods are pour point test, record viscosity vs. temperature, cold finger test, and yield stress value. Paraffin inhibitors can reduce significant volumes of wax deposition.

Paraffin inhibitors have a similar molecular structure to wax. It co-precipitates or co-crystallises with a wax crystal by replacing wax molecules on the crystal lattices. It imposes steric hindrance on paraffin crystals, which interferes with the proper alignment of the new incoming paraffin molecules to the degree that growth terminates. Although this can reduce the wax deposition rate and prevent wax deposition on the pipe wall, it cannot prevent wax precipitation [8].

A crystal modifier may also adsorb onto the paraffin crystal, thereby preventing agglomeration or deposition. Commercially, the crystal modifiers are referred to as pour point depressants [14].

Typical crystal modifiers are polyethylene, copolymer esters, ethylene/vinyl acetate copolymers, olefin/ester copolymers, ester/vinyl acetate copolymers, polyacrylates, polymethacrylates and alkyl phenol resins [8].

Polymers have been successfully used as crystal modifiers in some areas and their use should be expanded as more effective polymers are developed. The polymer's molecular weight also has an influence on the pour point depression. Short or lower molecular weight polymers may cause little disruption to the wax crystal agglomeration and growth, while very long and high molecular weight polymers can interact with the molecule itself instead of with the wax structures. This interaction reduces the rate of wax

formation, leading to the formation of softer wax that is easy to transport [12,15-17].

Molecular simulation methods have developed a better understanding of the interaction mechanism of polymers; for example, the inhibition of wax formation and growth has been examined using poly octadecyl acrylate, where it interacts with the wax molecules and prevents long chain wax formation [18,19].

Pedersen and Rønningsen [20] tested 12 different commercial pour-point depressants and concluded that viscosity reduction in crude oils with wax was the highest within the temperature range of 10 to 25°C. Wei [21] provided a review of several newly developed wax-crystal modifiers such as ethylene-vinyl acetate, polyethylene-poly (ethylene-propylene), poly (ethylene-butene), and poly (maleic anhydride amide co- $\alpha$ -olefin), and determined that the performance of wax-crystal modifiers was a strong function of their ability to cocrystallize with wax. Therefore, in addition to the structure of the wax-crystal modifier, its composition is also significant. The efficiency of wax-crystal modifiers is increased by using them with solvents [21].

### Dispersants

Dispersants are similar to surfactants in their molecular structure. One end of the molecule is attracted to the paraffin, but the other end is soluble in either oil or water, depending on the phase in which the paraffin is dispersed. Dispersants break wax crystals up into much smaller particles and reduce the rate of wax deposition, preventing it by minimising wax adhesion to the pipe wall [8]. Alkylaryl sulfonate is an example of a dispersant.

Dispersants do not dissolve paraffin deposits but break them up into larger needle crystals which precipitate pack better with less interaction and can be reabsorbed by the oil stream. Therefore in case of squeeze jobs dispersant effectiveness partially depends on formation permeability. Dispersants may diffuse several times its own weight in paraffin but their application range is not wide as solvents. Typically added into lower water cut systems and used in cold climates where paraffin inhibitors cannot be applied. Application: continuous into production system, batch treated into tanks, squeeze jobs. Oil dispersants selection method is a tank bottom test [9].

Hoffmann and Amundsen [22] found that about 60%-90% of wax thickness is reduced by applying different inhibitor concentrations during experimental work investigation. The presence of a small concentration of inhibitors, such as poly ethylene-co-vinyl acetate (EVA) and poly maleic anhydride-alt-1-octadecene (MA), can coalesce with wax crystals and interfere with their growth [23,24].

### Chemical solvents

Solvents increase the solubility of wax in oil and dissolve already deposited wax. The solvents most commonly used today include xylene, toluene, benzene, carbon tetrachloride, trichloroethylene, perchloroethylene, carbon disulfide, white or unleaded gasoline and pine-derived terpenes [8].

Chlorinated hydrocarbons of various types are efficient solvents because they are relatively inexpensive and have a high specific gravity. High specific gravity is an important factor that will help solvents penetrate and dissolve the paraffin deposits typically at the bottom of the flow section. The use of some of the

solvents mentioned above is problematic, however: chlorinated hydrocarbons cause poisoning of the downstream process, aromatic solvents have low specific gravities and it is difficult to use them on the well bottoms, they also have low flash points and handling becomes difficult, while carbon disulphide is highly effective but also highly flammable with toxic fumes [10,14].

Generally, solvents are used to remove existing deposits. Paraffin solvents are used in locations where it is impossible to use water and surfactant combinations. Because some crudes are too sensitive to surfactants and always form emulsions or the produced waters with very high concentration of total dissolved solids greatly limits the range of paraffin compounds available. Solvents are best applied to wells that have very little standing oil in the casing above the pump. This promotes a concentrated product at the problem source rather than a very dilute solution of oil and solvent if a large volume of oil is present in the casing [9].

They are useful toward dissolving only a specific weight of wax dependent on molecular weight (MW), pressure, and temperature [9,25]. Some of the commonly used chemical solvents to dissolve wax formations are carbon tetrachloride, carbon disulfide, kerosene, and diesel oil [9,10]. The advantage of using chemical solvents is that they are inexpensive and may not require complicated instrumentation. However, this method may be less efficient toward dissolving wax plugs with larger masses [3].

### Detergents

Detergents are class of surface active agents that work in the presence of water to water – wet paraffin particles, formation, tubing and flowlines. These formulas break up deposits and prevent them from re-agglomerating back together further downstream in the system. If well stimulation procedures such as acidizing or fracturing are planned, paraffin downhole deposition should be removed by paraffin dispersants and detergents prior to the stimulation. They can be carried by hot water, either fresh water or produced water. However, KCl water can be used if clay swelling is a problem. Deposit removal will also prevent the paraffin deposition from being pushed deeper into formation during the treatment. Emulsion stabilization tendency caused by paraffin in returning acid can be destroyed by paraffin compounds added to acidizing solution. Prior to addition to any treating fluids paraffin compounds should be checked for compatibility.

## THERMAL METHODS

### Hot fluid (Hot oil or Hot water)

Hot fluid (hot oil or hot water) method is one of several thermal methods of wax mitigation that have been used in the oil fields and it is one of the most-common methods used in the field [7,8]. Hot fluid is the method of injecting hot oil or hot water (approximately 65 to 150°C) down the well tubing or casing to melt waxes that restrict downhole equipment [3,9].

Crude oil for the operation should be checked for solids and cloud point. If the wax appearance temperature is above the bottom hole temperature or the volume of solids exceeds 1% then formation damage is likely, then hot oil should be replaced with hot water. Hot watering can be done with or without chemicals. By using water some hot oil problems listed below can be avoided as water contains no paraffin but other problems still exist. For instance,

chemical added to the water can disperse the wax but water itself will not dilute or dissolve paraffin [9].

The advantage of combined hot water surfactant treatment over hot oil: water is higher specific heat in comparison with oil, which allows water to be arrived at the site of deposition with a higher temperature. However, the wax cannot be melted out of the tubing below 500 feet and if the cloud point is high enough wax deposition can start far below 500 feet, and the hot oil/water treatment would remove only part of the deposition. Despite of that it is quite popular treatment among operation companies [9].

The biggest advantage is perhaps associated with it being a simple method and that it may not require complicated instrumentation, low costs, and immediate results. However, the effectiveness of hot oil/water injection depends on the location of wax in the tubing. Because the heat capacity of the injected liquid is much lower than the heat capacity of the well, the liquid starts cooling fast and may not be as effective when paraffin is at larger depths.

The disadvantages of hot oiling are [3,9]:

- It may cause pump and flowlines plugging.
- It may carry wax into the formation and cause permeability reduction.
- It may deposit paraffin in the casing.
- Safety concerns.
- Significant heating is required.
- Well damage by removing the lighter waxes and leaving the heavier waxes behind

### Downhole heaters

A continuous source of heat is used to melt paraffin or asphaltene deposits in the wellbore or on the tubing for a certain period, after which the melted material can be pumped up to the surface with oil production. The disadvantages of this method are high maintenance cost of heating system, availability of electric power [9].

### Exothermic or fused chemical reactions

This technique involves exothermic chemical reactions with controlled heat emission to remove wax deposits in pipelines. Fused chemical reactions undergo a delay before significant product formation. Nguyen et al. [26] performed a fused chemical reaction between sodium nitrite and ammonium chloride catalyzed by citric acid encapsulated in polymer-coated gelatin capsules. They suggested that because of the characteristic delay, a highly fused exothermic chemical reaction will produce substantial heat to melt and re-dissolve wax at the desired location [3,26]. Using the encapsulation technique, either the catalyst or one of the reactants is encapsulated. Thus, the release of the catalyst into the bulk solution is controlled. Therefore, the exothermic reaction between sodium nitrite and ammonium chloride was delayed by the controlled release of the encapsulated catalyst, which was citric acid. The polymeric coating on the capsule had to dissolve before the catalyst was released into the solution and heat was generated. The thickness of the polymeric coating determined the extent of delay of heat release.

Another significant example of wax removal using exothermic

reactions is the nitrogen-generation system. This is a novel technology to dissolve wax formed in pipelines, which has been developed, field tested, and commercialized by Petrobras Research Center. This method involves introduction of two inorganic salts and organic solvents to a line. Their chemical reaction generates nitrogen and heats the internal sections of a pipeline where wax has formed. The heat is used to dissolve the wax plug. It is then flushed out of the pipeline. The disadvantage of using exothermic chemical reactions as a method to mitigate wax formation is related to higher costs because of the requirement of expensive chemicals, catalysts, and polymer coatings. The chemicals used may also be toxic. Finally, exothermic chemical reactions are an indirect method of heat generation compared with direct methods such as hot oiling/watering [3].

### Thermal insulation and coating

One of wax mitigation methods is the thermal insulation of subsea flowlines and risers of the production wells. The insulation is needed to keep the steady state flow temperature 30°C above WAT over the field lifetime. On the other hand, it was reported that wax deposition can occur above the dead oil WAT in some systems. Therefore it was suggested keep the system temperature greater than 90°C above the dead oil cloud point. Because at the same pressure wax deposit temperature is always higher than WAT, and the average temperature difference is about 9.40°C. For example, Jiang Bin [15] mentioned that in order to find out the effect of pressure on wax appearance temperature, the WATs for live and dead oil from a same layer in Well K-1(K oilfield is located in the north of the West Branch of the East African Rift Valley) were tested at three different pressures, 10.6, 15.8, and 22.8 Mpa. It can be seen from Table 1, pressure has a significant impact on WAT, the WAT of live and dead oil both reduced as the pressure decreases. Compared with dead oil, the reduction of WAT of live oil is smaller over the same pressure drop. It can be seen from Table 1, at the same pressure, the WAT of live oil is about 8°C lower than that of dead oil, which demonstrates that dissolved gas suppresses the wax precipitation considerably [15].

Pipeline insulation can include external insulation coating or pipe-in-pipe flow lines and risers for ultra-deepwater system. Plugs may be melted if electrical pipe heating is installed [9].

Researchers have also studied the effect of plastic coatings on wax deposition. It was shown that plastic coatings decreased the weights of wax deposits by 30 wt% or more for high-molecular weight wax because of thermal insulation [27]. For their experiments, Patton and Casad [27] studied three different waxes: Cit-Con 350, Shellwax 200, and Cit-Con recrystallized heavy-intermediate wax. The recrystallized heavy-intermediate wax has a much-larger MW than the other two waxes and is representative of the natural paraffin deposits in pipelines. Recently, coating the internal surfaces of a pipeline with a new polymer, ethylene-tetrafluoroethylene (ETFE),

**Table 1:** Wax appearance temperature for live and dead oil at three different pressures [15].

Pressure/ MPa	Live Oil WAT/°C	Dead Oil WAT/°C	Temperature Difference/°C
10.6	56.77	64.92	8.15
15.8	58.91	66.73	7.82
22.8	60.11	68.74	8.63

has been reported as a useful method to inhibit wax formation. A test was conducted with three different pipes: a pipe with ETFE internal-plastic-pipe coating, a pipe with rigid polyvinyl chloride internal-plastic-pipe coating, and a steel pipe. The ETFE pipe with the least roughness showed the best results. Such surface treatments preclude the need for chemical injectors or storage containers for hot water/oil during heating operations. However, mitigation of wax by providing surface coatings may be more expensive than most other methods discussed [3].

## COMBINATION METHODS

### Mechanical-chemical treatment

The most economical solution may be a combination of paraffin inhibitor (pumped at a lower than sufficient rate) and pigging, especially for systems with high pigging frequencies. In contrast, if the pigging sufficiently removes wax deposition with little or no deferred production, then usage of paraffin inhibitors would be not necessary [9].

### Thermo-chemical treatment

This type of treatment can be applied to deposits that have changed their nature over a period of time and become more thermodynamically stable. For instance, SGNTM (Nitrogen generation system) treatment comprises of injecting the heat generating chemicals directly into the flow stream without interrupting it. Thanks to this technique significant production loss was prevented on some oil fields in Brazilian basin. Disadvantages: some techniques require accurate information on the location of wax deposit and its wax fraction [9].

### Wax mitigation by microbial treatment

Using microorganisms for wax mitigation, although not very widely used, has been successfully used on some fields of the Mehsana Asset of Oil and Natural Gas Corporation Limited [28]. Biosurfactant-producing bacterial cultures have been reported that aid in wax mitigation in pipelines. Strains such as the *Pseudomonas* species and *Actinomyces* species have been shown to reduce heavy hydrocarbon fractions and increase C15 to C20 fractions when crude oil was treated with these bacteria. Crude-oil properties were improved by lowering the WAT, thus making pipelines with flowing crude oil less susceptible to wax formation [29]. A bacterial strain, *Geobacillus TERI NSM*, has been identified that can help degrade crude-oil paraffin at high temperatures. Such bacteria degrade the paraffin under high-temperature, low-oxygen, and low-nutrient conditions while sparing low-carbon-chain paraffin [3,30].

Lazar et al. [31] studied a special bacterial consortium (SBC1) and reported that they were efficient in preventing and controlling solid- as well as semisolid-paraffin deposition. Although this is an innovative method, microbial treatment may only be used in wells that produce water and where the bottomhole temperature is lower than 200F. This is because the microbes used require water to survive and may not be able to withstand extremely high temperatures [3].

### Cold flow

Cold flow is the method of generating slurry of solid deposits in a controlled way such that they do not adhere to the pipeline

walls [32]. One of the earliest known cold-flow technologies was patented by Coberly [33]. Wax crystals typically form on the walls of a pipeline when the temperature of the wall falls below the WAT or the crystallization temperature of wax. Coberly [33] suggested that wax deposition may be retarded by reducing the temperature of the oil that contains wax to well below the crystallization temperature. It was also mentioned that by adding fine particles of resin with a melting point greater than the crystallization temperature of wax, the resin particles acted as nucleation sites for wax and would prevent deposition of wax crystals along the pipeline walls [33]. Merino-Garcia and Corraera [32] mentioned that the feasibility of cold flow could be validated by eliminating the temperature gradient and cold wall. Figure 4 shows the cold-flow scheme redrawn by the authors using the work by Merino-Garcia and Corraera [32] and White et al. [3].

Argo et al. [34] invented a similar cold-flow technology where hydrocarbons containing wax and other solid deposits such as asphaltenes, or any other precipitating solids, could be transported through pipelines [34]. This technology involves introducing hydrocarbons into a reactor, where they are mixed with a flow of cold fluid with a temperature lower than the crystallization temperature. Figure 5 shows a simple schematic of this technology, which is explained here. Warm oil containing dissolved wax enters the reactor. At the same time, cold oil/condensates containing small crystals enter the reactor. The small crystals in the cold oil may be carbonates, salts, wax, asphaltenes, or any other crystals

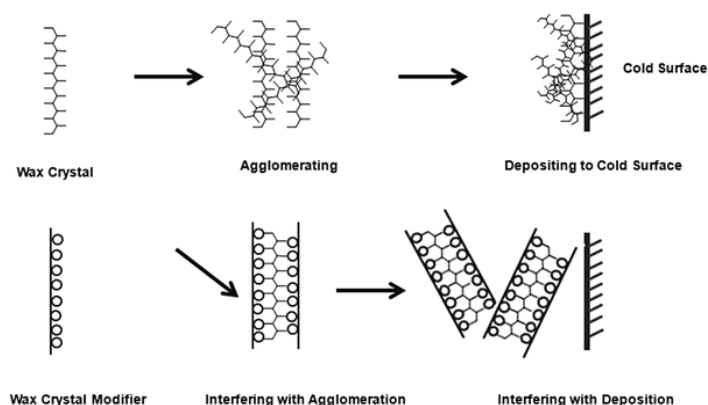


Figure 3: Schematic representation of wax crystal modifier co-crystallization with wax crystals [2,10].

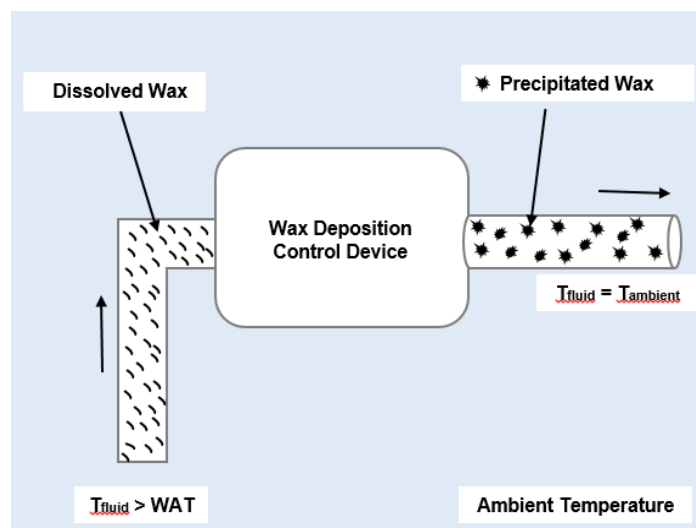
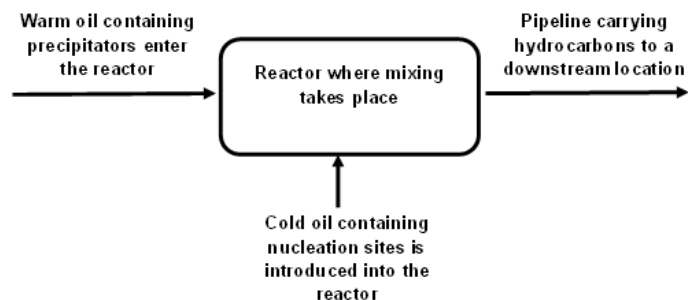


Figure 4: Cold-flow scheme [2].



**Figure 5:** Cold-flow method for transporting hydrocarbons containing wax [2].

that can act as nucleation sites. When warm oil is mixed with cold oil, the precipitators precipitate as small crystals on the nucleating sites and are carried by the flowing hydrocarbons without causing deposits or blockages. The extent of subcooling may be maintained either by enough cold liquid or by sufficient heating inside the reactor [3,34].

However, the cold-flow technology has not been implemented by the industry for field use. It has been a research and development project that has progressed to the stages of laboratory prototypes and pilot testing [3].

C-FER Technologies in Edmonton, Canada, have proposed the recirculation of cold oil to reduce the temperature of crude oil and thus inhibit wax formation on pipeline walls [10]. Figure 6 shows the apparatus from Al-Yaari [10] redrawn by White et al. [3]. Nenniger and Nenniger [35] reported a method of using cold, unheated oil for recirculation and for stimulating heavy-oil production. However, this method may not be suitable when wax has already solidified on the walls of pipelines.

### Choke cooling method

Knowles [36] developed a technology where a stream of gas and waxy oil was suddenly cooled by letting it pass through a choke to form wax/oil slurry. The slurry could be transported through pipelines without wax deposition along the pipeline walls. Figure 7 shows a conceptual representation of the apparatus redrawn by the authors using the work by Knowles [36]. However, creating the choke geometry may be expensive, and the method may not be effective when wax plugs already exist in a pipeline. A breakaway wax plug traveling with a high velocity may damage the choke region of the pipeline [3].

### The wax eater method

Using this technology by Kellogg, Brown, and Root and Halliburton, hot oil enters a flow loop when the ambient temperature is much lower and is maintained at lower than WAT. This encourages the formation of wax in oil but also reduces the oil temperature to approximately the seabed temperature. Thus, the wax dispersed in oil does not move toward the walls to accumulate there. The amount of recirculating fluid must be greater than the amount of oil that enters the flow loop [3,32]. Figure 8 shows the wax eater reproduced by the authors using the published work by previous researchers [10,32]. Like cold-flow technologies, the wax eater has not been used in the field yet [3].

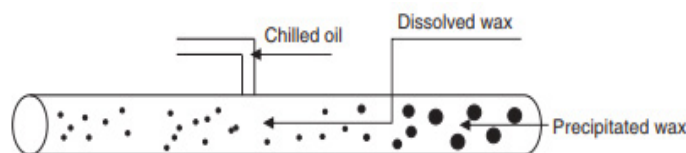
### Magnetic-fluid conditioning method

This is a novel technology in which a fluid exposed to a magnetic field causes changes in solids that are being carried or precipitated from that fluid. When the fluids in pipelines are directed across powerful magnetic fields, the growth of wax crystals is altered and therefore the formation of solids is inhibited. Magnetic conditioning is useful toward preventing clogging caused by wax and other solid deposits in wells and pipelines carrying oil. There are several patents that have been derived from this technology. However, this method will be more expensive than the conventional methods used because of its requirement of complicated instrumentation to maintain the magnetic field [2,3].

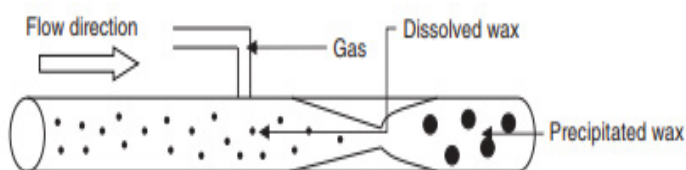
### Eco-wave TM treatment method (Baker Hughes)

It is chemical-free and environmentally friendly stimulation. This technology uses high-frequency radio waves and microwaves at low power to alter molecular bonds downhole, stimulating production increases by disrupting damaging deposits and improving reservoir wettability [9,37].

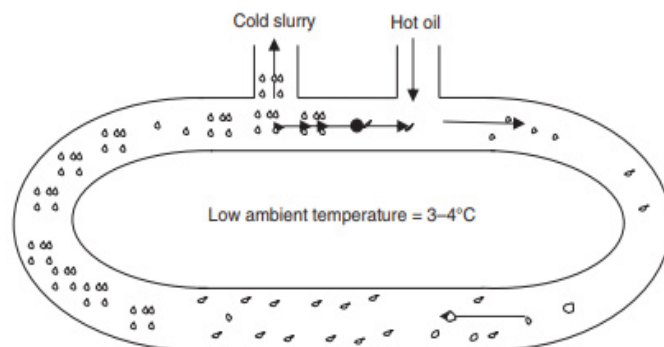
Equipment for a treatment consists of Ecowave unit, tuner, antenna system and portable power source. After candidate well selection and approve from operator the antenna is deployed in annulus or tubing at surface, and then attached to the Ecowave. System is powered and treatment begins for about 2 - 4 hours. The effectiveness of the technology was field-proved; with reported production increase from 20 to more than 120 percent and treatment longevity more than 60 days [2,9,38].



**Figure 6:** Cold-oil recirculation [2,3,10].



**Figure 7:** Choke cooling.



**Figure 8:** The wax eater.

## Ultrasonic waves treatment method

Towler et al. [39] presented a novel way for mitigating wax deposition in a wellbore or pipeline. The treatment concept is to attach a device generating one ultrasonic frequency (used frequency was 120 kHz) to the production tubing and produce one ultrasonic frequency thereby breaking wax molecule bonds and preventing the wax from depositing on the production tubing walls. The results of such treatment are increased flow rates and production efficiency. Further work is required to determine the optimum frequencies [9,39].

## Bacterial treatment method

It is been found that naturally occurring marine microorganisms, which have the ability to absorb paraffin, are able to remove effectively paraffin deposits or at least reduce the deposition over a certain time period [9,10]. Strata International has a bacterial product called PARAGONE which offers treatment programs that remove paraffin accumulations, inhibit corrosion or scale formation, and acts as emulsion breakers for production wells as well as for injection wells. The product is made of naturally occurring microorganisms suspended in a water-based solution that is pumped down the annulus.

The mechanism of PARAGONE involves two processes: 1) degradation of the paraffin and 2) surfactant, produced by the bacteria cause the paraffin to become soluble in the oil again. The PARAGONE decreases oil viscosity, cloud point, pour point and surface tension of oil to the rock grain, significantly improving oil recovery. The PARAGONE treatment procedure has been applied for more than 20 years in a number of oil fields with oils of different specifications. There has been no uncontrollable bacteria's cloning. The bacteria were feed with injected nutrients to control bacteria cloning on site. Once the nutrients injection is stopped, the bacteria disappear completely from the field. Generally, in the oilfield, the microbial products are batch treated and pumped into the well-bore annulus. New batches are injected periodically in order to maintain the size of the microbial colony [9,10].

Advantages: Non-pathogenic, non-toxic, non-carcinogenic, non-flammable, noncombustible, environmentally safe [2,9,10].

Disadvantages: corrosion or souring, treatment is limited to wells producing water and it suffers from the difficulty to control the process [9,40].

## Spiral flow method by Theyab

Theyab [1], mentioned that he after going through the literature accessed regarding use spiral flow as a mitigation method for wax deposition, he was noticed that a few types of research mentioned the spiral flow in different study areas; however, he did not notice any researcher before used spiral flow to reduce or mitigate wax deposition.

Spiral flows have a wide range of applications in various engineering areas, such as chemical and mechanical mixing and separation devices, chemical reactors, combustion chambers, turbo machinery, rocketry, fusion reactors and pollution control devices. Studying the mechanism of spiral flow is useful for promoting industrial and economic development because the spiral flow contains more energy, which plays an important role in the flow [41].

Spiral flow velocity distribution is unique; its tangential velocity

of almost linear distribution, which forms a tangential velocity, is conducive to the pipeline sediment 'spin float', thereby forming a high concentration of transport.

Theyab [1] generated spiral flow by inserting a twisted plate inside the test section of the pipe of his experiment, in order to increase the force of shear stress and shear dispersion that makes the wax molecules rotate and moved in the centre of the bulk (Figure 9). The twisted plate divided to 12.5 sections, each section equals to 12 cm and height 1 cm.

Spiral flow enhances heat transfer due to the increased velocity in the tube and the circulation of the fluid by centrifugal convection because the low density of the warmer fluid at the pipe wall is displaced into the cooler stream in the central region by centripetal force. This kind of transport mechanism decreases the wax deposition in the pipe wall, therefore, Theyab [1] considered spiral flow method as an important factor to remove wax deposition inside the pipes.

Theyab [1] studied in his experiments the influence of the inhibitor polyacrylate polymer (W802) at different concentrations, spiral flow, and the combination of polyacrylate polymer (W802) and spiral flow on wax deposition.

Figure 10 shows the effect of the mitigation methods of Theyab [1] on wax deposition volumes at a flow rate of 2.7 L/min, experimental time of 2 hours, and the ambient temperature was 4°C; it can be seen that the wax volume was 125 ml after running the experiment using just crude oil. The highest wax volume reductions were 75.2% by using the method of blending the effect of the spiral flow with the inhibitor at 2000 ppm; and reduced to 73.6% by using the method of blending the effect of the spiral flow with the inhibitor W802 at 1000 ppm.

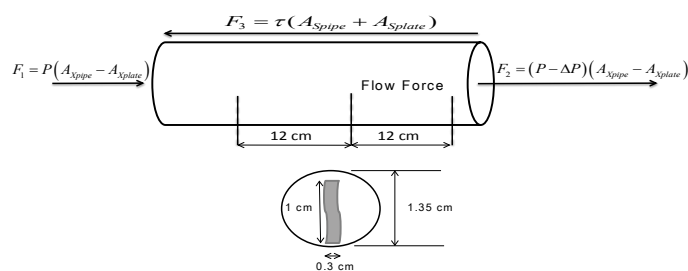


Figure 9: Spiral flow method by Theyab [1] to mitigate or prevent wax deposition.

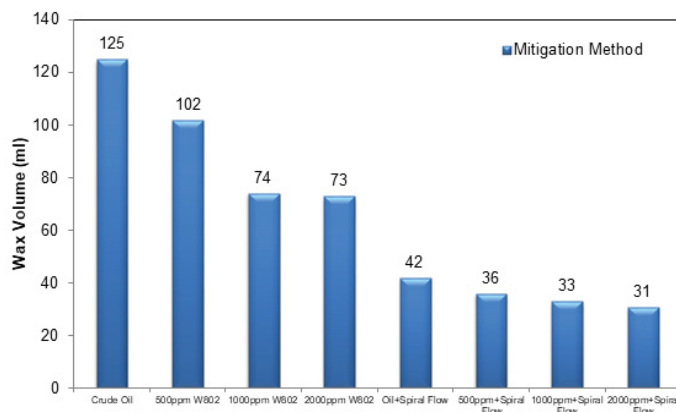


Figure 10: The effects spiral flow and the polyacrylate polymer on wax deposition volume at flow rate 2.7 L/min, experimental time 2 hours and the ambient temperature was 4°C.



This reduction occurs due to the double effect of the spiral flow, which increases the shear stress and moves the wax molecules to the pipe centre-line, and the inhibitor, which prevents the formation of a long chain of wax by enter the inhibitor molecules between the wax molecules. The difference between the two methods was 1.6%, so the first new inhibitor involving bending the spiral flow with 1000 ppm of the inhibitor is preferred because this method reduced the cost of the inhibitor used in the mitigation method.

Spiral flow method represents a second best method to reduce wax. This method reduced the wax volume to 66.4% and it works efficiently even at low temperatures due to increasing the shear stress and preventing the wax molecules from connecting with each other and depositing as long chains on the pipe wall.

The reduction of wax volume was 40.8% and 41.6% by using the inhibitor W802 at concentrations 1000 and 2000 ppm respectively; therefore the difference between the two percentages was 0.8%. The method of the inhibitor W802 at 1000 ppm is therefore preferred to that at 2000 ppm due to the fact that it reduces the economic cost of the inhibitor. While, at a concentration 500 ppm of W802 leads to reduce the wax deposition to 18%, due to this concentration of the inhibitor is not enough to prevent the wax formation and deposited on the pipe wall.

## DISCUSSION

If wax deposition cannot be prevented, then it is imperative to regularly remove accumulated wax from the inside of pipeline walls in order to prevent the total blockage of the line. Several methods have thus been developed for the removal of wax deposits, including complete blockages of pipelines. Traditional methods of wax removal in the petroleum industry have always had problems and limitations, and they include mechanical removal, the use of bottom hole heaters, the use of exothermic reactions such as that between magnesium bars and hydrochloric acid, and the use of paraffin solvents [42]. Research continues to be done to find the most efficient, cost-effective and safe methods of removing wax deposits and blockages. Furthermore, some researchers have worked on modelling the operating conditions necessary for the successful and safe restart of gelled pipelines, in which gelled waxy crude needs to be displaced using applied pressure [42]. The most effective way of dealing with the problem of wax deposition in crude oil pipelines would be to prevent it from occurring in the first place. Different methods have been investigated of inhibiting the deposition process. These include the heat insulation of subsea pipelines to actually inhibit precipitation by keeping pipeline temperatures as high as possible, the internal coating of pipelines with plastics, and also methods of preventing wax deposition on pipeline walls, such as the use of chemical inhibitors [2,42].

Many oil companies prefer chemical additives in analysing the economics of waxy crude oil production in cold environments, considering this the best solution to reduce wax deposition in pipelines due to chemical additives does not need to stop production for cleaning the pipe but it considers as an online mitigation method. There is currently no universal type of inhibitor can be used for all kinds of crude oil due to the varying properties of crude oils. This is an investigation to understand the wax deposition problem, because of the universal inhibitor may solve the wax deposition problem and create more problems such as (corrosion) due to varying properties of crude oils and the different climate.

A universal solution would be a both convenient and cost effective response to the current demand. Presently, most of the companies have their personalised technique to tackle the wax deposition. This is not very practical as oil viscosity changes depending on the geology and geographical location. If spiral flow technique is adopted universally in the correct way, it will help to reduce the amount of investment as well as man power to achieve better results. Researchers have used various different types of chemical inhibitors, such as polyethylene, ethylene/vinyl acetate copolymers, copolymer esters, ester/vinyl acetate copolymers, olefin/ester copolymers, polymethacrylates, alkyl phenol resins, xylene and toluene, studying their effects on wax appearance temperature, wax content, pour point, and crude oil viscosity using analytical methods, to evaluate the suitable inhibitor for the waxy crude oil that provides the desired results in preventing wax deposition. A small number of researchers have used an experimental flow loop to study and determine dynamically the efficiency of wax inhibitors on wax deposition inside the pipe. The difference between the analytical methods and the experimental flow loop systems is the experimental conditions used in the flow loop deposition test affected the performance of paraffin inhibitors, indicating that temperature gradients (i.e., oil temperature and inlet coolant temperature) must be optimized to achieve the highest reduction in wax deposition. While, the experimental conditions in the analytical methods can be controlled, such as pressure, temperature, and shear rate, providing accurate results in the analytical of wax inhibition. Adeyanju and Oyekunle [12] investigated the effect of groups of acrylate ester copolymers of varying alkyl side chains as wax inhibitors during the flow of crude oil in the flow loop. Wax inhibition percentages of 25-55% were obtained at high coolant temperatures above 20°C at a concentration of 5000 ppm of the inhibitor. Hoffmann and Amundsen [22] found that about 60%-90% of wax thickness was reduced by applying different concentrations (125, 250 and 500 ppm) of the commercial inhibitor, and using silicon as an insulation material during experimental work investigation. In the previous studies, even though many different types of chemical inhibitors have been used at different concentration, at different inlet coolant temperatures, there is still wax deposit on the pipe wall due to the researchers missed investigate the effect of combining the chemical inhibitors on wax deposition. A small number of researches mentioned using the spiral flow and studied its effects in different areas, however, Theyab [1], used the technique of spiral flow for the first time as a wax mitigation method. He built an experimental rig to study the wax deposition thickness under the single phase and to study the impact of some factors, such as flow rate, pressure drop, inlet coolant temperature, crude oil temperature, oil viscosity, time, shear stress, polyacrylate polymer and spiral flow, that influence and control on wax deposition process. The spiral flow was generated by inserting a twisted plate inside the pipe and examined in the test section of the pipe in order to increase the shear rate and shear dispersion and mitigate wax deposition. The results illustrated that the reduction in wax deposition was 100% after using the influence of bending spiral flow with polyacrylate polymer at a concentration of 1000 ppm and 2000 ppm at different time and flow rates, and the ambient temperature was 33°C. The reduction in wax deposition was 100% after using the effect of bending the spiral flow with the inhibitor at a concentration of 500 ppm at flow rate 4.8 L/min, and the reduction in wax deposition was 94% at the same concentration and flow rate 2.7 L/min.

## CONCLUSION

Wax deposition on the hydrocarbon pipelines of the cold environment considers as one of the main fluid flow assurance challenges that face the petroleum engineers. Wax can precipitate as a solid phase on the pipe wall when its temperature drops below wax appearance temperature. It results in the restriction of crude oil flow in the pipeline, creating pressure abnormalities and causing an artificial blockage leading to a reduction or interruption in the production. This work represents the important mitigate methods to reduce or prevent wax deposition in the hydrocarbon production systems around the world, such as the chemical, mechanical, thermal methods, or a combination between them, microbial treatment, cold flow, cold-oil recirculation method, choke cooling method, the wax eater method, magnetic-fluid conditioning method, Eco-wave TM treatment, ultrasonic wave treatment, bacterial treatment, and spiral flow method. Many oil companies prefer chemical inhibitors in cold environments, considering this economic way and best solution to reduce wax deposition in pipelines due to chemical additives does not need to stop production for cleaning the pipe but it considers as an online mitigation method.

It can be concluded that the decent understanding and managing of wax deposition phenomena before it happens is strongly required in order to overcome the challenges in production and transportation of pipelines in the cold environment.

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