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## Crude oil and the problem of wax deposition on pipeline systems during transportation: A review

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### Abstract

Crude oil, the world's major source of energy, is obtained from the earth as a Newtonian fluid and needs to be transported to refineries for further processing. Pipeline transport has proven to be the most efficient, environmental-friendly and cost effective of all modes of crude oil transportation from subsea production sites. However the formation and deposition of waxes (mainly paraffinic and asphaltenic components) along pipelines remains one of the greatest flow assurance problem in the petroleum industry. This is aided by attainment of wax appearance temperature (WAT), the crude's hydrocarbon contents and rheological properties, and the production conditions amongst others. The deposited waxes clog the pipeline, reduces the flow diameter, converts the behavior of the fluid from Newtonian to non-Newtonian, decreases throughput, causes more work on pumps and other process equipment, increases energy consumption, and ultimately raises the cost of production thereby decreasing profits. It also leads to several downtimes and in extreme cases can cause permanent shut down of facilities. Several studies have been done to understand the nature of crude oil waxes and the various techniques for solving this problem. This paper takes a critical look at crude oil and reviews the current state of research into the causative factors, deposition mechanisms and remediation methods including the thermal, mechanical, biological and chemical techniques. At the end there is a conclusion and further research on the use of biological techniques (microorganisms) has been advised herein.

**Keywords:** Crude oil; Wax; Wax deposition; Deposition mechanisms; Pipelines; Wax remediation techniques

### 1. Introduction

Crude oil and its derivatives are essential to humans. It serves as a fuel source and also a raw material in the manufacture of important industrial and domestic petrochemicals. Crude oil occupies an important part of our daily lives as it is currently the world's major source of energy [1]. There is a steady increase in the global demand for crude oil as a result of its role as the number one energy source and raw material for the manufacture of a wide variety of products for daily living [2]. It accounts for 37% of the world energy supply [3]. Crude oil and its derivatives are among the most traded commodities on earth [4]. Amongst the derivatives from crude oil are gasoline (Premium Motor Spirit), Automated Gas Oil (AGO), Aviation fuel, Dual Purpose kerosene (DPK), Bitumen and a host of other products that are beneficial to man. Fuels from crude oil greatly influence changes in the industrial and transportation sectors thereby increasing its consumption. Many modern industries, such as the agro-allied, refining, plastics, textile, agro, food, petrochemical industries, etc., utilize and depend on crude oil and its by-products for their daily production activities [1]. Also, these fuels find usage in energy generation and supplies power generating companies (Gencos) [5].

Crude oil is obtained from the earth's crust and transported to refineries. Oil and gas field exploration fields are often afar off from production sites and are becoming less accessible. This is mostly due to the depletion of conventional oil

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reserves and so oil production has to be done in deep-water zones which have low temperatures [6]. In such cases, there is need to transport the crude oil from the exploration site to the refining facility. The various means of transporting crude oil and petroleum products include: the use of oil liners, rail transport and pipeline transport [7].

The use of pipelines has proven to be better off than other modes of transportation. The advantages of transporting crude oil through pipelines include increased transport capacity, small amount of transport traffic, reduced energy consumption, low wear and tear and less vulnerability to climatic conditions [8]. It is also best suited for long distances and for inland transportation as it ensures supply even to remote places. Johnson [9] states that the use of pipelines is the most reliable and safest mode of crude oil transportation as more than 95% of the fluid is transported effectively to their final destination. Aside these, the land where pipelines are buried can be used for further purposes. In the United States of America, crude oil and petroleum products are transferred majorly by pipelines as pipelines account for 58% of the transport mode while rail transport accounts for 31% [7]

The transportation of crude oil through pipelines is often always faced by a familiar challenge – the formation and deposition of waxes. This arises due to the complex nature and constituents of crude oil, which range from simple gases to large molecules of paraffins and asphaltenes which have large molecular weight [10], reduced temperature as a result of heat loss [11], its nature as a viscous liquid [2], the rheological properties of crude oil [12], the operating conditions of the production field, climatic and environmental conditions amongst others. These waxes cause lots of financial and technical damages and increase the costs of production [13]. It remains a critical operational challenge for the petroleum industry [14].

In light of the challenges above, this work therefore looks at the nature of crude oil, the causes, mechanisms and effects of wax formation and deposition on pipelines during transportation, and the remediating steps for this problem. The aim is to explore current and evolving trends made by researchers in this field while taking a look at what the future holds with regards to the mitigation of this problem.

## 1.1. Nature and rheology of crude oil as a fluid

### 1.1.1. Nature of crude oil

Crude oil is a viscous liquid obtained from the Earth's crust as a result of exploration [2]. It is a naturally-occurring fluid that consists thousands of hydrocarbons that are grouped into the four major classes of saturates (aliphatics e.g paraffins), resins, asphaltenes and aromatics [15], and fractions of other organics. It consists of n-alkanes (polar and non-polar) ranging from C17 to C36 [3] and normal alkenes with carbon chains: C1 to C120 [16]. Aside hydrocarbons, crude oil also contains sulfur, nitrogen, and traces of metals. Metals usually found in crude oil include iron, nickel, vanadium and copper [3]. The molecular weight of crude oil ranges from 800 – 2,500 [17]. The formation of crude oil is aided by natural decomposition of dead matter buried in the ground millions of years ago and supported by pressure [18].

Crude oil, extracted by exploration and drilling, comes out as a viscous fluid with mud and other unwanted purities. It may be gotten onshore or offshore. But most productions today are done offshore. It comes out with natural gas (lighter than crude oil and sits above) and saline water (which is denser and sinks below) [19]. Between 50% – 97% of the composition is hydrocarbons, 6% - 10% of it is oxygen, nitrogen and sulfur, while metals like nickel, vanadium, iron and copper accounts for less than 1% [18].



**Figure 1** Gradual shift in crude oil production from onshore to offshore in the late 20th century [3]

1.1.2. Classification of crude oil

Crude oil is often characterized by the hydrocarbons in it. Paraffins account for a greater percentage of hydrocarbons in crude oil [20]. Because of the different hydrocarbon contents in them, crudes from different parts of the world often have varying colors and viscosities. Crude oil has been classified by the American Petroleum Institute (API) into heavy, medium and light oils based on their API gravity, a dimensionless constant [1]. This measure is used to evaluate the weight of a crude oil sample in comparison with water [21]. Very heavy crudes have API gravities less than 100, heavy crudes have API gravities between 100 – 300, medium crudes have gravities between 300 - 400, while light crudes have gravity above 400 [17]. The equations for evaluating the specific gravity and API gravities are given below:

$$S.G = \frac{\rho_{oil}}{\rho_{water}} \dots\dots\dots (1)$$

$$API = \frac{141.5}{S.G} - 131.5 \dots\dots\dots (2)$$

Where,  $\rho_{oil}$  = density of the crude oil sample, in kg/m<sup>3</sup>;

$\rho_{water}$  = the density of water, in kg/m<sup>3</sup>;

S.G = the specific gravity of the crude oil sample;

API = American Petroleum Institute gravity.

Another method of classification is the Watson characterization factor,  $K_w$ , and correlation index, CI. According to Al-Dahhan and Mahmood [17], this method is one of the oldest crude oil characterization methods. The methods for obtaining the Watson Characterization factor and correlation index are obtained from equations 1 and 2 below:

$$K_w = \frac{(T_B)^{\frac{1}{3}}}{G} \dots\dots\dots (3)$$

$$CI = 87552(T_B) + 473.7(G) - 456.8 \dots\dots\dots (4)$$

Where,  $T_B$  = average boiling point of crude oil in Rankine;

G = specific gravity at 60°F.

Crudes with high paraffinic contents have  $K_w$  in the range 12.5 – 13.0 while the  $K_w$  for naphthenic (cyclic) contents are usually in the range 10.5 – 12.5. The higher the CI values for a crude, the more aromatic and naphthenic contents it has while the lower the CI values, the higher the concentration of paraffinic hydrocarbons in the crude.

1.1.3. Rheology of crude oil

An inquiry into the rheological properties of crude oil is necessary in determining the proper method(s) of preventing the problem of wax formation in the transportation of crude oil through pipelines [10]. There is need to adequately establish the viscosity-temperature relationship accurately to determine the pump ability of crude oil and petroleum products [22]. It plays a vital role in flow processes through pipelines as it is a key determinant of productivity, oil recovery, and other performance indices [23].

Rheology is described as the science that deals with the deformation of matter in terms of viscosity, elasticity, and plasticity under applied forces (stresses and strains) [24]. A fluid is a substance that continually deforms when acted upon by external forces or shear stress. The behavior of fluids broadly classified them into two: Newtonian and Non-Newtonian Fluids. While Newtonian fluids obey the Newton’s law of viscosity and exhibits a linear relationship between shear stress and shear strain, the Newtonian fluid does not [10]. The Newton’s law of viscosity is shown in the equation below:

$$\tau = \eta\gamma \dots\dots\dots (5)$$

Where,  $\tau$  = Shear stress, in N/m<sup>2</sup>;

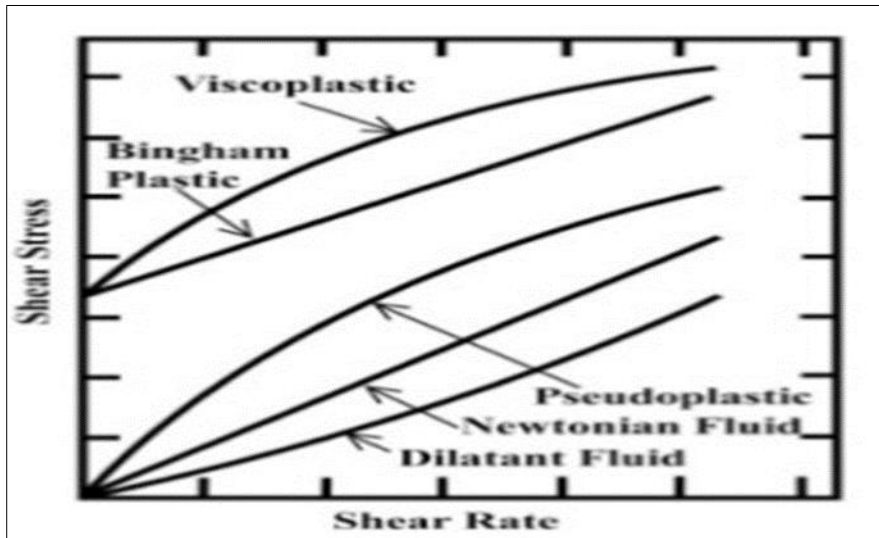
$\gamma$  = Shear rate, in s<sup>-1</sup>;

$\eta$  = kinematic viscosity, in cm<sup>2</sup>/s.

Non-Newtonian fluids have different sub-classes which depend largely on the response of the fluid’s viscosity to the duration and magnitude of the applied shear force. The classes of non-Newtonian fluids are: Thixotropic fluids, Rheopectic fluids, Bingham Plastic fluids (which some crude have been reported to behave as), Pseudo-plastic fluids, and Dilatant fluids [10]. A non-Newtonian fluid often does not have constant viscosity [22]. They generally obey the power law equation below:

$$\tau = K\gamma^\eta \dots \dots \dots (6)$$

Where,  $\tau$  = Shear stress, in N/m<sup>2</sup>;  
 $\gamma$  = Shear rate, in s<sup>-1</sup>;  
 $\eta$  = kinematic viscosity, in cm<sup>2</sup>/s;  
 K = Proportionality Coefficient which may assume any value.



**Figure 2** Fluids and the relationship between shear stress and shear strain [10]

Crude oil behaves as a Newtonian fluid at high temperatures since waxes in it are in a molten state [25]. It is pertinent to note that crude oil extracted from the Earth’s crust exhibit Newtonian properties [22]. During transportation through pipelines, waxes are formed and crude oil changes from a Newtonian to a non-Newtonian fluid which hinders flow thereby reducing throughput [26]. This confirms the relationship between crude oil temperature and viscosity and their collective importance as reported in Taiwo et al. [24].

The flow of crude oil (especially through pipelines) experiences different flow regimes which may be laminar, turbulent or even transitional. But whichever flow regimes (patterns) takes place, optimum throughput is always desired [2]. The three regimes are differentiated by the Reynold’s number (Re), a dimensionless constant. The Reynold’s number is evaluated using the equations below:

$$Re = \frac{\text{inertial force}}{\text{viscous force}} = \frac{\text{fluid and flow properties}}{\text{fluid properties}} \dots \dots \dots (7)$$

It can also be restated as:

$$Re = \frac{\rho ul}{\eta} = \frac{ul}{\mu} \dots \dots \dots (8)$$

Where,  $\rho$  = density, in kg/m<sup>3</sup>;

$u$  = fluid velocity, in m/s<sup>2</sup>;  
 $l$  = length of the pipe, in m;  
 $\eta$  = dynamic viscosity;  
 $\mu$  = kinematic viscosity.

Laminar flows have Re lesser than 2,000. Here, flow is orderly and there is little or no lateral mixing. It takes place in low velocity profiles. However, it is not desirable in the transportation of crude oil and petroleum products because it would yield lesser throughput [10]. Turbulent flows have Re above 4,000 and are characterized by high velocity profiles. There’s a high rate of lateral mixing and haphazard motion in this regime which often results in eddies, vortices, and drags [25]. This is the kind of flow pattern used by pipeline operators as it guarantees good throughput [22]. Transitional flow often occurs when Re is between 2,000 – 4,000. Fluid flow in this regime may show properties of laminar or turbulent flows.

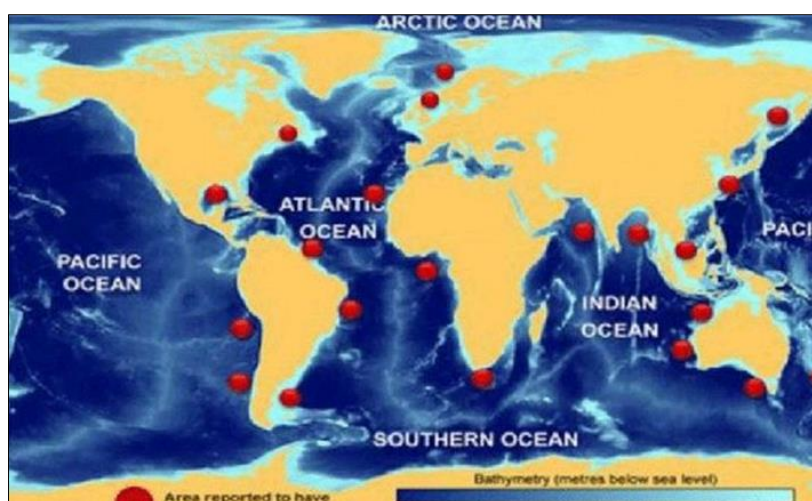


**Figure 3** Orientation of fluid molecules during (a) Turbulent flow and (b) Laminar flow [27]

### 1.2. Wax formation problem in crude oil transportation through pipelines

Wax formation and deposition remains one of the greatest problems faced in the petroleum and hydrocarbon industry [13]. Among all flow assurance issues, the formation of waxes during the production and transportation of crude oil remains the greatest issue [28]. It affects numerous oil companies across the world and can even cause production sites to shut down [29]. At shutdown, the estimated cost of replacement and downtime is pegged at \$30,000,000.00 (thirty million dollars) [11]

The problem of wax solution is amplified by the fact that most oil production sites are moving deeper and deeper offshore [13]. This trend is sure to continue into the foreseeable future as the ocean seabeds have lots of deposits yet untapped [6]. Because of the numerous threats it poses, petroleum waxes continues to receive attention as researchers seek to find a lasting solution.

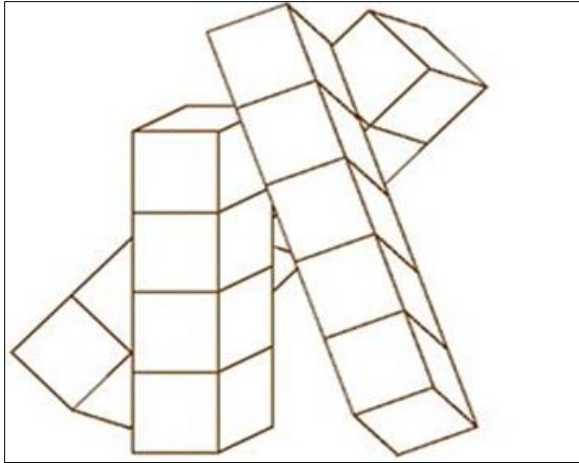


**Figure 4** Areas where wax deposition has been reported to occur [3, 30]

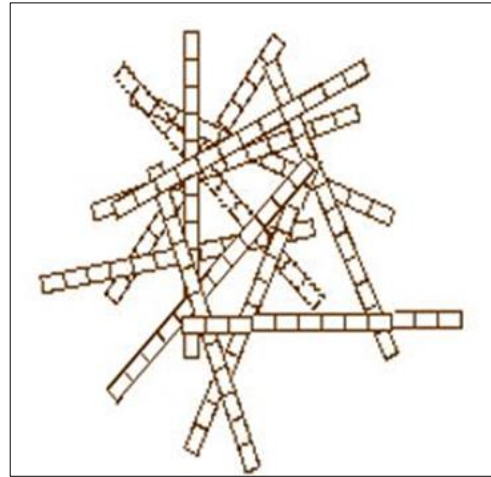
#### 1.2.1. Nature of crude oil waxes

Waxes in crude oil refer to a mixture of hydrocarbons having high molecular weights [6]. They are long-chain alkanes found in crude oil [10]. Crude oil waxes are mostly paraffinic waxes (macrocrystalline waxes) [15] and may also contain some amounts of naphthenic hydrocarbons (microcrystalline waxes) [16]. These are the two groups of petroleum waxes [25]. The amount of waxes in crude oil differs and is usually a function of the region it is obtained from. Crude oil may contain up to 33% wax or more [20]. The Niger Delta crude exhibits waxiness to the tune of 30 – 45% [24]. Anisuzzaman et al [1] posits that paraffinic waxes differ from asphaltenic waxes in that paraffinic waxes are non-polar and aliphatic while asphaltenic waxes are polar and aromatic. Despite their differences, both contain varying amounts of high boiling point hydrocarbons, can aggregate in solutions, and are soluble in crude to a certain degree [15].

Paraffinic waxes consist of straight, branched and cyclic alkanes which may exist as a liquid or solid in room temperature [6]. They have carbons with atoms: C18 – C36 [24]. El-Dalatony et al [15] reports that paraffinic (macrocrystalline) waxes have heat capacities of about 2.14 – 2.9 J/gK and densities of around 900 kg/m<sup>3</sup>. They form platelet-like or needle-like crystals on cooling to low temperatures and have an evaporation point of 40 – 600C [3]. The molecular weight of paraffinic waxes ranges from 350 to 600. Microcrystalline waxes, on the other hand, often result from naphthenic hydrocarbons having carbon atoms in the range of C30 – C60 [16]. They are also known as amorphous waxes and Iso-paraffin waxes [25]. These waxes have higher molecular weight and melting point compared to the paraffinic waxes [15]. They precipitate into amorphous-like structures [6]. Their molecular weight is in the range 300 – 2,500 causing them, alongside other properties, to form tiny crystals on precipitation [3]. These waxes are thinner and smaller than macrocrystalline waxes that form stronger and thicker gels on precipitation [15].



**Figure 5** Macrocrystalline waxes [27]



**Figure 6** Microcrystalline waxes [27]

Waxes aren't noticeable at the initial stages because at reservoir conditions (i.e temperatures between 70 - 150°C and pressures > 2,000 psi), they are soluble in crude oil [11]. Wax formation in crude oil is mostly caused by a temperature differential between the crude oil system and the environment. Waxes can begin to form when the inner temperature of the pipeline falls below the Wax appearance temperature (WAT) [20]. This is the temperature at which original equilibrium conditions responsible for wax solubility in crude oil changes and the first wax starts to precipitate as a result of the reduction in solubility [24]. When a fall in temperature occurs, the molecules in the oil begin to lose energy causing a reduction in motion. This causes the molecules to bind with each other in clusters that overtime grow in size [3]. Wax precipitation doesn't have any noticeable dependence on pressure [20]. Crude oil experiences some changes in properties as a result of these waxes. It would change into a non-Newtonian fluid and would have high effective viscosity [3]. In the precipitation process, higher molecular weight hydrocarbons would appear first onto the pipe wall before those with lower molecular weight [31]. Aside temperature differential, Theyab and Yahya [30] identified some factors that impact the rate of wax precipitation such as: crude oil nature and composition, oil temperature, viscosity, production time, flow rate, coolant temperature, and shear stress. Igwilo et al [25] also posits that pipe roughness, operating temperatures, well depth, oil cloud point, pour point, rate of evolution of gas, pipe roughness, and production practices are other factors that can affect the rate of wax precipitation.

Wax formation process follows the two main steps of i) nucleation and ii) crystal growth [1]. The first stage involves its precipitation from crude oil when environmental factors favor it. The first precipitate, often called wax nuclei, prepares the ground for crystallization and growth. Nucleation is further divided into primary and secondary nucleation [32]. At the primary nucleation stage, homogenous particles are formed spontaneously near the pipe walls in a three dimensional (3-D) crystal lattice containing some oil [29]. Secondary nucleation involves the coming together of units of precipitates formed in the primary nucleation stage [3]. On reaching a certain stage, the formed wax crystals begin interacting with each other and begin to grow as time progresses until they become large enough to clog the pipe [14]. Anisuzaman et al [1] lists the various methods of ascertaining the physical parameters of waxy crude oil as are given in the table below:

**Table 1** Crude oil properties and evaluation methods [1]

Property	Methods
Wax Appearance Temperature (WAT) (also known as Cloud Point)	ASTM Method, Differential scanning calorimeter (DSC) method.
Wax Deposition	Cold spot, cold disk and cold finger tests.
Wax Formation	X-ray diffraction
Pour Point	ASTM Method
Flow Ability	Viscometry, yield stress, flow loop test
Wax Morphology	Cross-polarized microscopy (CPM), Scanning Electron Microscope (SEM)

1.2.2. Mechanism of wax deposition

This simply refers to the whole processes through which waxes accumulate in the inner wall of the pipe. These processes involve the formation of a separated solid phase (gel layer), deposition, and growth of the layer [6]. Wax deposition can result from already occurring precipitated waxes [27]. The deposits first attach themselves to the surface of the pipe in direct contact with the oil and eventually grow from there. Wax deposition is further divided into two stages: i) wax gel formation and ii) aging [27].

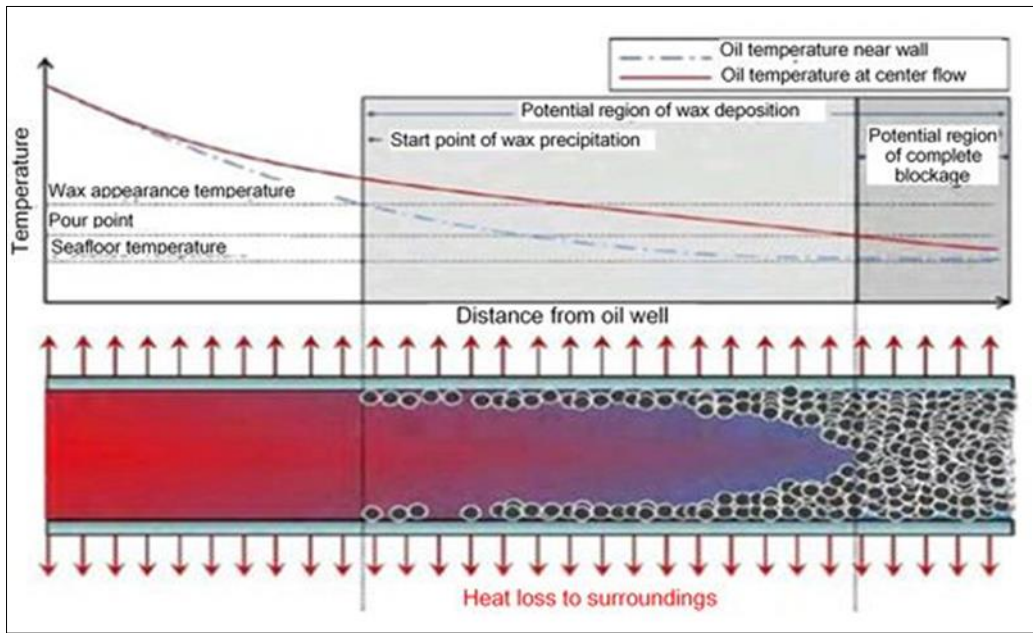


Figure 7 Wax deposition process [33]

Several researchers have put forward a number of mechanisms to explain wax deposition which includes molecular diffusion, gravity settling, Brownian diffusion, and shear dispersion [29]. Another mechanism put forward is the thermal diffusion (also called Soret diffusion) [34]. However, the processes have not been entirely validated [6]. There is a need to constantly study these mechanisms in order to get a better understanding for the mitigation of the wax deposition problem in crude oil transport through pipelines.

Molecular diffusion

Almost every researcher that has studied the mechanisms of wax deposition supports the claim that molecular diffusion is the most dominant of all [11] This mechanism involves the transfer of molecules of the wax from a region of higher concentration to a region of lower concentration as a result of temperature, crude oil viscosity, and the size of the molecules [1]. Lonje and Liu [33] posit that the radial temperature gradient between the center and the walls of the pipes is the main causative factor for this mechanism. The principal driving force here is the concentration gradient formed at the pipe center and its walls due to this radial temperature gradient [11] During crude oil transportation (especially in offshore regions), the temperature of the pipe wall is usually lower than that of the center due to contact with the seabed. A radial gradient of temperature is formed which leads to precipitation of wax molecules in the colder region further causing a radial concentration gradient [34]. The molecules of the wax would subsequently migrate to the pipe walls with the aid of molecular diffusion since solubility decreases with temperature [6]. Lonje and Liu [33] states that the rate of mass transfer to the pipe wall can be estimated by Fick’s law as:

$$\frac{dM_w}{dt} = \rho_w D_w A_w \frac{dc}{dr} \dots \dots \dots (9)$$

- Where,  $M_w$ = Mass of deposited wax on pipe wall, in kg;
- $t$  = time, in seconds;  $\frac{dM_w}{dt}$  = rate of wax deposition on pipe wall, in kg/s;
- $\rho_w$ = density of the solid wax, in kg/m<sup>3</sup>;
- $D_w$  = diffusivity of liquid wax, in m<sup>2</sup>/s;
- $A_w$ = surface area for wax deposition, in m<sup>2</sup>;

$\frac{dC}{dr}$  = concentration gradient of wax over the radial symmetry of the pipe, in  $m^{-1}$ .

### Gravity settling

According to Theyab [29], the precipitated wax molecules are denser than the surrounding crude oil liquid phase. When these molecules are not interacting, they would settle down at the bottom of the pipe under the influence of gravity causing deposition [6]. However, this mechanism has been described by past researchers as insignificant to wax deposition especially in subsea conditions [6, 33, 34].

The expression for finding the settling velocity,  $V_g$ , of the wax molecules is given as [6]:

$$V_g = \frac{d^2(\rho_p - \rho_f)g}{18\mu_f} \dots \dots \dots (10)$$

- Where,  $V_g$  = wax molecules settling velocity, in m/s;
- $d$  = molecule diameter, in meters;
- $\rho_p$  = particle density, in  $kg/m^3$ ,
- $\rho_f$  = density of the crude oil fluid, in  $kg/m^3$ ;
- $g$  = acceleration due to gravity, in  $m/s^2$ ;
- $\mu_f$  = the viscosity of the crude oil fluid, in Pa.s.

### Brownian diffusion

The Brownian diffusion mechanism involves the haphazard movement of wax molecules as a result of their collision with thermally agitated molecules of the crude oil [6]. It occurs in regions where the crude oil flows below the cloud point [33]. There is a concentration gradient created by this which aids the net migration of wax molecules to the region of lower concentration – the pipe wall [22]. The net migration, caused by bombardment by the excited oil molecules, is in form of Brownian or irregular motion to the pipe walls [34]. Olajire [6] states that Fick’s law can also be used to model transportation of the molecules towards the region of lower concentration thus:

$$\frac{dM_B}{dt} = \rho_w D_B A_w \frac{dC}{dr} \dots \dots \dots (11)$$

- Where,  $M_B$  = Mass of deposited wax on pipe wall as a result of Brownian diffusion, in kg;
- $\frac{dM_B}{dt}$  = rate of wax deposition on pipe wall as a result of Brownian diffusion, in kg/s;
- $D_B$  = Brownian diffusion coefficient, in  $m^2/s$ .

Theyab [29] gives the equation for finding the Brownian diffusion coefficient as:

$$D_B = \frac{RT_a}{6\pi\mu_{solvent}aN} \dots \dots \dots (12)$$

- Where,  $R$  = the universal gas constant (8.314 J/Kmol);
- $T_a$  = the absolute temperature, in Kelvin;
- $N$  = Avogadro’s number ( $6.022 \times 10^{23} \text{ mol}^{-1}$ );
- $a$  = Brownian particle diameter, in meters;
- $\mu_{solvent}$  = the solvent’s dynamic viscosity, in Pa/s.

Aiyejina et al [34] acknowledged that many researchers rejected Brownian diffusion as a relevant mechanism for wax deposition. This is due to theoretical inconsistencies as what is expected directly contrasts Brownian motion itself. Since the temperature at the pipe wall is lower than that of the bulk medium, there should be higher precipitation of wax at the inner wall of the pipes causing wax build-up in the pipe region which negates the principles of Brownian motion [6]. Nevertheless, some researches acknowledge its role in wax deposition [3, 33].

### Shear diffusion

Shear dispersion is more pronounced in laminar flow regions of crude oil where small solid molecules travel towards the surrounding bulk fluid with an average speed thus causing shearing effects on the fluid [6]. These shearing effects would lead to the formation of a shear field. According to Lonje and Liu [33], the shear field is often at the stream-line



center of the fluid flow where slower-moving molecules collide with those moving at high speed. This shear field, where shear flow occurs, contributes to wax deposition through lateral motion of the molecules immersed in it [34]. During the interaction (collision) between molecules moving at different speeds, there are transient displacements as the molecules tend to bend around each other and return to their original streamline [3]. Since there are many molecular interactions, a net lateral particle displacement would result [29]. Olajire [6] gives the rate of deposition of wax due to shear dispersion as:

$$D_s = \frac{r^2 \gamma_s C_w}{10} \dots\dots\dots (13)$$

Where,  $D_s$  = shear dispersion coefficient, in m/s;  
 $r$  = the particle radius, in meters;  
 $\gamma_s$  = oil shear rate, in  $s^{-1}$ ;  
 $C_w$  = concentration of the precipitated wax at the wall.

Thermal (soret) diffusion

Soret diffusion is the mass transfer of wax molecules and their deposition in the pipe walls as a result of the existence of a temperature gradient within the pipeline system [34]. The temperature gradient acts as the driving force for the mechanism to occur. The effect of this diffusion in the deposition of wax is often seen to be negligible by researchers [6]. However, there is need for its incorporation because diffusion is dependent on temperature also. Thus, modeling the diffusion of wax molecules in terms of its molecular and thermal aspects gives a more correct approach to the issue of wax deposition mechanism [34].

1.2.3. Wax detection and estimation techniques

To be able to curb the effects of wax deposition in crude oil transportation through pipelines, there is need to estimate its buildup in pipelines. This is necessary to forestall sudden and/or total shutdown as a result of partial or total blockage of the pipeline flow area with wax [35]. Several methods propounded by researchers for wax detection and estimation include the pressure drop method, the heat transfer method, and the pressure wave propagation technique [26]. Theyab [21] also suggested the pigging technique, while Aiyejina et al [34] suggested the use of a special caliper alongside a video camera on remotely-controlled submersible equipment for measuring the external diameter of the pipeline after it is pressurized.

The pressure drop method

The pressure drop method is based on the concept of increasing pressure drop along the pipeline resulting from a decrease in the hydraulic diameter caused by wax deposition [36]. It can be used to estimate wax thickness without restart or depressurization the pipeline [21]. This method is the most commonly used wax buildup estimation technique not just in pipelines but also in wells [26].

The equation for calculating wax thickness from the wax equation presented in Theyab and Diaz [22]:

$$d_i - 2\delta_w = \frac{2c\rho L}{\Delta p_f} \left(\frac{\mu}{\rho}\right)^n \left(\frac{4Q}{\pi}\right)^{2-n} \dots\dots\dots (14)$$

Where,  $d_i$  = the diameter of the pipe, in meters;  
 $\delta_w$  = the wax thickness;  $L$  = the pipe length;  
 $\Delta p_f$  = the pressure drop;  
 $\mu$  = the viscosity of the crude oil;  
 $\rho$  = the density of crude oil;  
 $Q$  = the volumetric flow rate.  
 For laminar flow,  $c = 16$  and  $n = 1$ . While for turbulent flow,  $c = 0.046$  and  $n = 0.2$ .

Sousa et al [26] also gives the equation for finding the pressure drop along a pipeline as:

$$\Delta P = \frac{fL\rho V^2}{2D} \dots\dots\dots (15)$$

Where,  $\Delta P$  = the pressure drop, in Pascal;  
 $f$  = Moody hydraulic friction coefficient (for Newtonian fluid  $f = 64/Re$ );

L = length of the pipe, in meters;  
 D = the inner diameter of the pipe, in meters;  
 $\rho$  = fluid density, in kg/m<sup>3</sup>;  
 V = velocity of fluid, in m/s;  
 Q = volumetric flow rate (m<sup>3</sup>/s).

The heat transfer technique

This method compares the coefficient of heat transfer in deposit layers before and after the wax appearance [26]. A convective heat transfer takes place between the layer of the deposited wax and the crude oil fluid. This ultimately leads to the transfer of heat to the pipe wall [22]. The total heat transfer includes the summation the resistance of the thermal resistance due to conduction through the wax layer and the heat transfer resistance from the crude oil to the surroundings through the pipe wall [21]. The estimate of the wax deposit thickness can therefore be expressed as [26]:

$$\frac{T_f - T_o}{q_o} = \frac{1}{h_w} \frac{r_o}{r_i} + \frac{r_o}{k_p} \ln \frac{r_o}{k_p} + \frac{1}{h_o} \dots \dots \dots (16)$$

Where, T<sub>f</sub> is the bulk fluid temperature in the pipe;  
 T<sub>o</sub> = outside pipe wall temperature;  
 q<sub>o</sub> = heat flux through the outside pipe wall;  
 r<sub>o</sub> and r<sub>i</sub> = the outside and inside radius of the pipe;  
 k<sub>p</sub> = thermal conductivity the pipe wall;  
 h<sub>o</sub> = heat transfer coefficient from the outside pipe wall to environment.

After the formation of the wax deposits, it becomes imperative to consider convective heat transfer from the bulk fluid to the deposits and conduction through the waxy layer [26]. The equation now becomes:

$$\frac{T_f - T_o}{q_o} = \frac{1}{h_w} \frac{r_o}{r_i - \delta_w} + \frac{r_o}{k_w} \ln \frac{r_i}{r_i - \delta_w} + \frac{r_o}{k_p} \ln \frac{r_o}{r_i} \dots \dots \dots (17)$$

Where, h<sub>w</sub> = the heat transfer coefficient from the flowing fluid to the wax layer;  
 k<sub>w</sub> = the thermal conductivity of the wax deposit;  $\delta_w$  = the thickness of the wax layer.

The pressure wave propagation technique

This technique utilizes pressure waves to detect blockages, and also predict the sizes, across the pipe cross-section. It involves the propagation of pressure waves through the pipeline and determination of the results using reflected wavelets [26]. The equation for determining wave severity is given as:

$$1 - \frac{A_B}{A} = \frac{2P_r/P_i}{1 + P_r/P_i} \dots \dots \dots (18)$$

Where, A<sub>B</sub> and A = the cross-sectional area of the pipe with and without blockage, respectively;  
 P<sub>i</sub> = incident acoustic pressure;  
 P<sub>r</sub> = reflected pressure from the blockage.

The pigging (direct) technique

Although not used widely in most subsea conditions, it is still used widely in single phase flow and low pressure conditions [21]. This technique involves passing a sphere through the pipe cross-section and measuring the volume of the wax removed [29]. Metal spheres are mostly used in this technique.

1.2.4. Effects of wax deposition

Petroleum waxes have a negative effect on the transportation of crude oil some of which are highlighted below:

- Wax deposition can result in the restriction of crude oil flow in the pipeline thus creating pressure abnormalities and leading to a reduction or interruption in production [22].
- The growth of crude oil wax crystals plug the inner wall of the pipe, covers it with wax layer resulting in extra burden on the pumping system [2]

- It ultimately leads to higher pumping cost [15].
- It reduces the allowable flow diameter of pipelines [25].
- Deposition of wax crystals also leads to formation damage near the wellbore, reduction in permeability, changes in the reservoir and pipeline fluid rheology as a result of the phase separation [29].
- It increases the energy usage needed for crude oil transportation due to the need for increased pressure in the pipeline to maintain constant flow rate [1].
- The precipitation of wax is responsible for changes in the waxy crude oil composition and properties, including the gelation of oil and an increase in viscosity [29].
- Another major problem is the high yield stress experiences when restarting of the pipeline after prolong shut down period due to the developed gel and wax structure [2].
- It increases capital, operational costs and maintenance costs [10]
- Wax formation leads to low productivity of the wells and pipelines [26].
- It leads to loss of production due to periodic shutdowns for maintenance and replacement resulting from the blockage of pipes [3].
- In an extreme case, it can cause a pipeline or production facility to be abandoned [6].
- It leads to tremendous loss in profit as a result of blockage of flow lines [32].

Overall, wax formation leads to wastage of valuable resources that would have been used for other important ventures.



**Figure 8** Cross-section of a pipe with deposited wax [3, 10, 33, 35, 37]

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## 2. Material and methods

### 2.1. Remediation of wax deposition in pipelines

There exist various methods for preventing and removing wax formation in crude oil transportation through pipelines. These are known as wax remediation methods. A variety of wax deposition control and remediation methods have been practiced by most oil production companies [1]. The frequently used methods are the thermal, mechanical (pigging), biological, and chemical methods [10].

#### 2.1.1. Thermal methods

This method involves using heat to keep the temperature of the bulk fluid in the pipeline above the wax appearance temperature (WAT) [3]. The heating can be done at different stations along the pipeline route [10]. The concept behind this method is to maintain temperature in the crude oil system for reducing wax buildup [35]. The temperature should however be watched in other not to coke the crude oil which can damage the wellbore [6]. The various thermal methods include: hot oiling, hot water treatment and direct heating [1]. The use of insulators can also be regarded as a thermal technique [37]. Aiyejina et al [34] also presented cold flow as a type of thermal remediation method for wax in crude oil.

### Hot oiling

Hot oiling involves the heating the oil to higher temperatures during which the waxes melts and then pumping down the hot oil into the well tubing for it to further melt the waxes in its way [6]. This process may be followed by the addition of a wax dispersant to ensure the melted waxes are well dispersed with the crude oil [3]. Despite it being one of the most popular wax removal methods, it isn't generally used in subsea conditions due to its expensive nature and the high risk of causing permeability damage if melted waxes enter the formation [27]. It is best suited for short distance transportation of crude oil [10].

### Hot water treatment

The use of hot water or steam for melting waxes has been reported in many literatures. Hot water has lots of advantages compared to the use of hot oil [37]. Water is readily available thus the process is cost effective [3]. Due to its higher heat capacity when compared to oil, the solvent arrives at the deposition site with a higher temperature [27]. Water also has little or no contaminants that may exist in the oil [6]. However, there is need to add surfactants to the water to boost wax dispersion due to solvency effects [34]. There is also the risk of corrosion and emulsion problems [6].

### Direct heating

This method involves the passage of huge quantity of current along the walls of the pipe to generate heat thereby causing the wax in the bulk fluid to melt [6]. This method is the most suitable method for subsea conditions as it constantly keeps the temperature of the fluid above the WAT [3]. It can solve flow assurance problems because of the possibility of controlling the temperature of the formation zone. It however not cost effective due to the exorbitant cost of heating and high consumption of electricity [27].

### Pipeline insulation

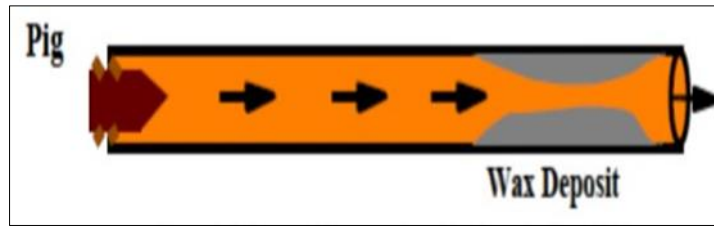
Ahmed et al. [10] also proposes the use of good thermal insulators in pipelines to avoid heat loss and keep the temperature below cloud point. The insulating material is installed in direct contact with the oil in the pipeline. There are lots of insulating materials that can be used for this process. However, not many of them possess the required chemical resistance, mechanical strength and cost effectiveness [26]. Alnaimat et al [35] suggests the use of plastics as insulators to shield temperature drop in the bulk fluid. Although not quite popular, but its use has been reported and recommended by researchers [37]. Some of the commonly used plastics are isocyanurate, polyurethane and ethylene tetrafluoroethylene (ETFE) amongst others [26].

### Cold flow

Cold flow technique involves lowering the temperature of the bulk fluid in the pipeline to equal that of the surrounding seabed in order to eliminate the temperature gradient that would have existed between them [34]. The principle behind cold flow technology is to allow the wax deposits to buildup in the bulk fluid system and flow with it rather than the pipe wall [6]. Cold flow can be used even in temperatures below the cloud point [33].

#### 2.1.2. Mechanical (pigging) method

The mechanical or pigging method refers to the use pipe inspection gauges (commonly known as PIGs) to scrape off the precipitated wax on the pipe wall [34]. Pigs are used extensively in the petroleum industry in the cleaning of crude oil pipelines [10]. It remains by far the most used wax removal technique (especially in offshore conditions) [3]. The pig, with a diameter smaller than the internal diameter of the pipeline, is launched from a device known as the pig launcher [37]. When launched, it is driven the oil pressure and knocks off wax buildup along the pipe wall. Pigs may be attached to wireline units or sucker rods to knockoff wax precipitates as the well is pumped. To make the pigging operation easy, most pipelines have double flow line designs [1]. Pigging is often very efficient in wax removal but it requires proper prediction of deposition rate on the pipe wall [10]. This method has some disadvantages however. A huge wax deposit from scraped wax may accumulate and plug the pipe downstream [11]. There may also be a process breakdown when the wax becomes excessively thick or when there is a reduction in the needed pressure to push the pig. This can make it difficult to remove the pig thus leading to shutdown of the entire pipeline system [6]. To help address these issues, bypass pigs were invented. Aiyejina et al [34] states that the wax breaking force of these bypass pigs increases as the oil content decreases. While it increases with an increase in the wax thickness layer.



**Figure 9** The pigging process [10]

### 2.1.3. Biological method

The removal of petroleum wax by biological method has been studied extensively by researchers in recent years. The goal is to discover and/or develop a strain of micro-organism (especially bacteria) that can utilize the wax as their carbon and energy source [6]. If this is successful, a large amount of the wax would be degraded thus reducing wax deposition in pipeline systems. Rana et al [38] showed the existence of bacterium capable of degrading crude oil wax and in developed systems with ample nutrients and carbon source, could serve as a better remediation method than pigging. Etoumi et al [39], in their work on the use of *Pseudomonas* bacteria for the mitigation of wax deposition in pipelines, discovered that the bacteria could serve as an emulsifier in the crude oil system. Their research also showed the bacteria worked well in reducing the concentration of long-chain hydrocarbons (especially those with carbon atoms above 22) and performed faster in the first 7 days. This was noticed because of the reduction in viscosity and the WAT. Sood and Lal [40] also studied the wax degrading ability of *Geobacillus* TERI NSM bacteria in conditions of low nutrients, low oxygen and high temperatures. It was discovered that this bacteria can degrade crudes with high molecular weight while it has little or no effect on those with low molecular weight. Adlan et al [4] also studied the ability of thermophilic bacterial strains to degrade paraffin waxes at 70°C. They used 11 distinct bacteria strains of *Geobacillus kaustophilus*, *Geobacillus jurrassicus*, *Parageobacillus caldxylosilyticus*, *Geobacillus stearotherophilus*, and *Geobacillus thermocatenulatus*. Some of the strains were able to degrade as much as 70% of wax in 3 days. Although the biological method is evolving, it however has its bottlenecks such as oxidation, souring and the occurrence of bio-corrosion [6].

### 2.1.4. Chemical method

This involves the use of chemical additives to remedy the situation of wax formation in pipeline systems. The concept is to add a material in definite quantity to help reduce the WAT or disperse the formed wax [10]. It does not require shut down of production facilities [3]. The chemicals used are solvents, wax crystal modifiers, dispersants and surfactants [15]. They are grouped into three (3) namely pour-point depressants (PPDs), wax inhibitors (wax crystal modifiers) and wax dispersants [32]. These materials have the same goal but operate in different ways [26].

#### Solvents

Solvents have the ability to dissolve the deposited wax at the pipe walls till it becomes saturated and loses its capacity to dissolve further [1]. The efficiency of solvents depends on the operating temperature, pressure and the molecular weight of the wax [3]. Solvents come in handy when a combination of surfactants and water can't be applied [27]. Amongst the commonly used solvents are carbon disulphide (CS<sub>2</sub>), carbon tetrachloride (CCl<sub>4</sub>), benzene, toluene, perchloroethylene, white or unleaded gasoline and other chlorinated hydrocarbons. However, the call for environmental protection has led to the use of Terpene, a biodegradable and less toxic chemical, with great ability to dissolve organics [6]. It can be used on its own or in combination with other solvents. The use of solvents has one disadvantage which is the occurrence of solvents with low specific gravity [6]. Specific gravity is needed so that the solvents can penetrate to the bottom of the flow section and dissolve the precipitated waxes [37]. Chlorinated hydrocarbons can help in this case and are relatively inexpensive but they can poison the downstream flow section [3].

#### Wax crystal modifiers

According to Anisuzzaman et al [1], wax crystal modifiers are polymeric compounds having wax-like hydrocarbon chains (similar in structure to crude oil waxes) and also has a polar portion. The hydrocarbon chains form the non-polar portion of wax crystal modifiers. They function by bonding with the wax's hydrocarbon molecules to form an assemblage on the crystal lattice [41]. Some portions of the crystal lattice are filled with molecules of the chemical alongside those of the wax by co-precipitation and co-crystallization. With this, they can effectively reduce the yield value, pour point and viscosity of the crude [37]. The alteration of the wax crystal structure would hinder its growth ultimately reducing the crude's cloud point [1]. The success rate of wax crystal modifiers depend on the nature of the crude, the production process and conditions, and the chemical's chemistry [6]. It has been discovered by researchers

that wax crystal modifiers can reduce wax thickness to the tune of 60 – 90 % depending on the concentration added [41].

#### Pour point depressants (PPDs)

Pour point depressants, also known as flow improvers or drag reducing agents, are polymeric chemicals that interact with the crude molecules and halts the potentiality of wax crystal formation [32]. They act to stop waxes from forming the 3-D lattices while ensuring the flowability of the crude. Their tail ends have n-alkyl chains which enable them to reduce the viscosity, yield stress and pour point [6]. The molecular weights of these chemicals exceeds 5 million parts per million (ppm) in terms of concentration [5]. With the right amount of PPD, agglomeration down the pipe tube will be inhibited [30]. However, they do not totally stop wax formation but only delays its precipitation and hardening thereby allowing them to be swept in the pipeline flow [32]. Amongst the commonly used PPDs are polymethacrylates (PMAs), olefin copolymers, alkylated polysterine, vinyl ester copolymers amongst others.

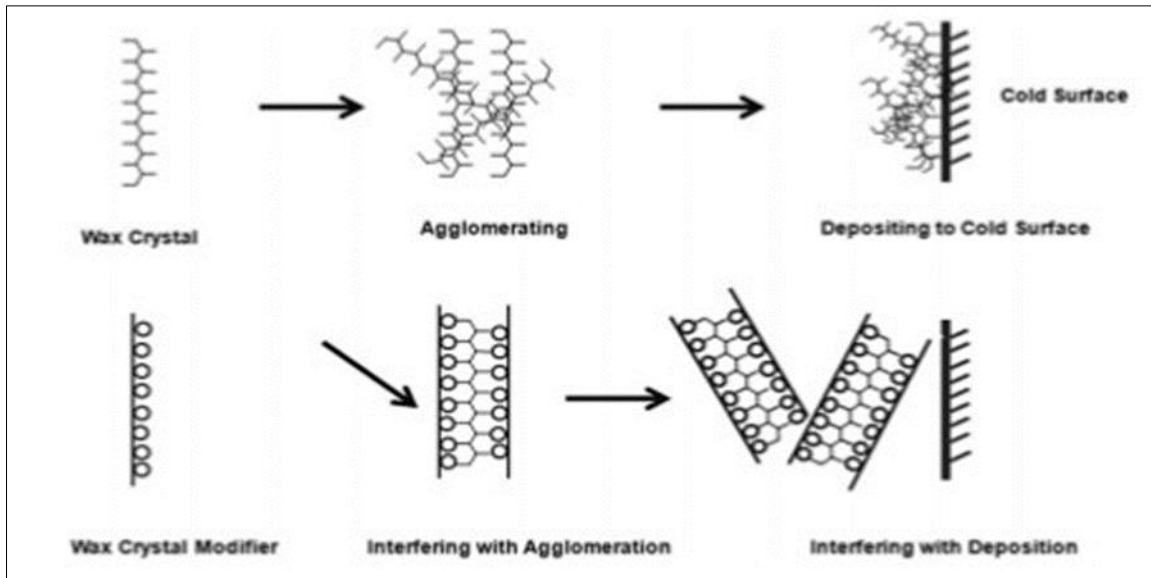
#### Dispersants

Wax dispersants are generally taken as a sub-class of surfactants, a class of chemicals used to clean pipelines where wax deposition occurs [30]. Wax dispersants are agents that disperse wax crystals along the body of the fluid. They do this by forming a layer on the pipe wall where the waxes stick and can easily be sheared off by the flowing fluid [28]. Their ability to break up waxes also helps reduce oil viscosity and reduce the emulsification ability of the wax [3]. Dispersants are often used in low concentrations and can be applied in batches or continuously [27]. They are better suited for cold climates that most other wax inhibitors as a result of their low pour point [6]. They are also relatively cheap (since they are used in small quantities) and easy to manufacture [37]. However, cheap surfactants perform better when mixed with fatty amine ethoxylates, alkyl sulfonates, amongst other alkoxyated products [6].

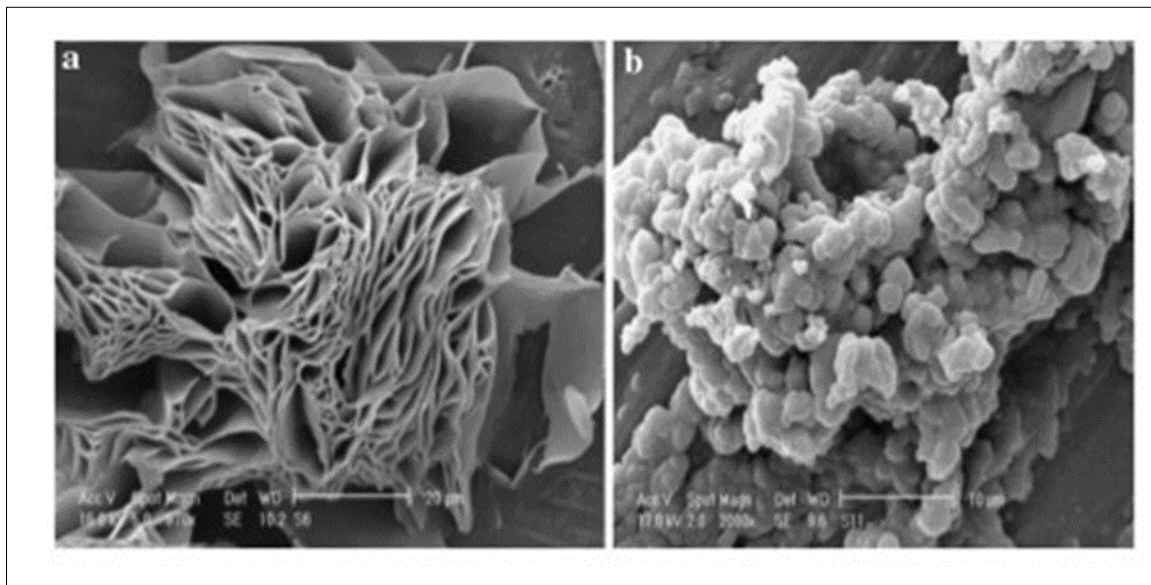
In summary, some common chemicals used in remediating wax formation and deposition, are highlighted below:

**Table 2** Some chemicals used in wax remediation

Chemical	Class	Researcher
Ethylene Vinyl Acetate (EVA) polymer	Wax crystal Modifier	[41, 42]
Triethanolamine (TEA) co-polymer	Emulsifier and Surfactant	[5]
Polyacrylate polymer	Wax inhibitor	[22]
Xylene	Dispersant	[2]
Kerosene	Solvent	[2]
n-Hexane	Depressant	[2]
Alkyl Acrylate Copolymer	Depressant	[1]
Maleic Anhydrides Copolymer	Dispersant	[1]
Poly(ethylene-butene) (PEB)	Wax Inhibitor	[41]
Poly (methyl methacrylate) (PMMA)	Wax inhibitor	[42]



**Figure 10** Action of flow improvers in waxy crude oil [6, 26, 37]



**Figure 11** SEM images of wax before and after addition of flow improvers [41]

### 3. Conclusion

The transportation of crude oil from production sites to refineries is faced by the recurrent problem of wax precipitation and deposition. Wax precipitation is caused by a drop in temperature, the nature (composition and viscosity) of the crude, the flow rate, shear stress, pipe roughness and production conditions amongst others. The precipitated waxes crystallize and are deposited on the pipe wall leading to great changes in the properties of the crude thus converting it to a non-Newtonian fluid. This leads to reduced flow ability, increased stress on process equipment, formation damage, increased energy consumption, low output, increased cost of production and low profits, and in extreme cases, the shutdown of production facilities. This review has evaluated the nature of the two major types of crude oil waxes and the wax deposition mechanisms of which the molecular diffusion mechanism is generally accepted by researchers. It also looks at the various methods of wax remediation including the thermal, mechanical, biological, and chemical techniques. To be better positioned to effectively solve this problem, it is advised that more research on the modeling of wax deposition using field scale data be carried out instead of laboratory scale data. It is also advised herein that more research should be done on the use of biological techniques in remediating the wax deposition problem. Microorganisms

that can effectively utilize waxes as a food source would do well in depleting waxes as the crude flows in pipelines. For the time being, a combination of two or three wax remediation techniques can be is also advised.

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## Compliance with ethical standards

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### *Disclosure of conflict of interest*

The authors declare that they have no conflict of interests.

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