
Application of Wax Prediction Model to Electrical Heat Tracing

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ABSTRACT

Reservoir hydrocarbon fluids usually contain heavy paraffin that may form solid wax phases at low temperatures. Problems associated with wax formation and depositions are a major concern in production and transportation of hydrocarbon fluids. The problem of wax deposition is even more pronounced in offshore production platforms and in very cold regions of the world such as the Alaska North Slope (ANS). Due to the rising world energy demand and depletion of conventional onshore fields, much of the world's recent hydrocarbon discoveries is found offshore. However, the ambient temperature in these locations is considerably lower than the wax appearance temperature [WAT]. Therefore, wax is more readily deposited, resulting in reduced productivity, increased pressure drop in flow lines, and general loss in production. Over the years, considerable effort has been directed by the industry and the academia towards generating reliable experimental data and developing thermodynamic models for estimating wax phase boundaries. Moreover, different techniques of solving the problem of wax deposition have been devised, but most of these methods are reactive, instead of proactive. One of the new methods of solving the problem of wax deposition is the method of electrical heat tracing. This method has been found to be very effective and efficient as it solves, not just the problem of wax deposition, but also other flow assurance problems such as hydrate formation. However, its greatest shortcomings are its high prohibitive cost and long distance viability. Hence, this work looks at how wax prediction models can be utilized in proactively solving the problem of wax deposition, using a modified electrical heat tracing technology, in the most economical way possible.

KEYWORDS: WAT, WDT, thermodynamic model, electrical heat tracing, paraffin

Introduction

The problem of wax deposition is as old as the petroleum industry. The term wax refers to a complex mixture of high molecular weight alkane (also known as paraffin) of the structural types, namely straight chains, branched chains and cyclic alkanes. They are usually called paraffin because they have little affinity for other substances. That is, because they are saturated hydrocarbons, they are not very reactive. The figure below shows different structures of paraffin (from waxes and asphaltines by geochemical services).

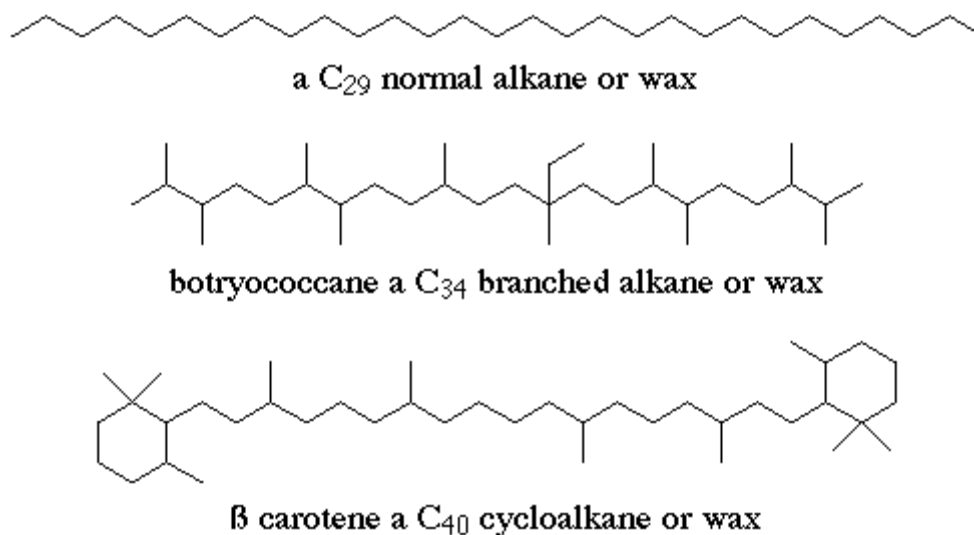


Figure 1.1 structure of paraffin

This class of hydrocarbons is natural constituents of all crude oil systems and natural gas condensates. So long as they are in solution they pose no problem to the crude oil production system. However, as the temperature and pressure of the crude oil drops due to heat and pressure losses in the flow line, the wax will begin to precipitate out of the solution.

Effect of Wax Deposition

Every crude oil system has its cloud point. That is, the temperature at which the first element of wax begins to appear on a cooled crude oil system. The appearance of wax crystals could lead to wax crystallization and may result in wax deposition. These deposits accumulate in the wellbore, tubing, surface flow lines and storage facilities; thus creating very significant production problems. Wax deposition is more pronounced in subsurface platforms and in very cold regions of the world such as the arctic regions. With increasing world energy demand and depletion of conventional onshore fields, exploration and production companies have had to face up to the highly unfavorable and difficult task of drilling and producing in these most challenging regions of the world.

One of the biggest challenges they have had to face so far is how to get the produced crude oil to the surface in these very cold climates. This is often referred to as the problem of flow assurance. Wax deposition is one of such problems. Wax is easily deposited since the WAT (wax appearance temperature) is much higher than the ambient temperature. In fact, whole platforms have had to be abandoned because of the problem of severe wax deposition. In the Niger Delta oil province, according to a research carried out by Sulaimon et al in 2009, a particular field having a recurrent case of wax deposition lost about 1500 BOPD during the 2007 production year. Considering the price of oil in that given year, then the magnitude of the problem we are dealing with becomes even more glaring.



Figure 1.2 Picture showing verity of wax deposition

In the Lasmoo field in the UK, wax deposition was so severe and frequent that the entire field was abandoned at a cost of over \$100,000,000 (Singh et al., 2000; Nguyen et al., 2001). In truth, the real cost of wax deposition is enormous. This value cannot be ascertained with certainty. According to Elf Aquitaine, the production down time cost for a period of forty days due to wax removal processes is about 25million US dollars. The cost of hiring divers to remove a blocked section of a subsea flow line is kept at 5million US dollars. Truly, a significant chunk of the operating expenditure is spent on keeping wax from blocking the flow line.

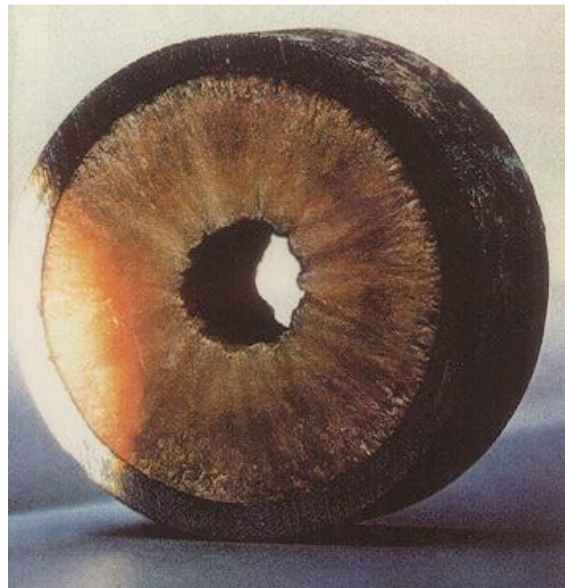


Figure 1.3 Picture showing Wax deposit reducing the effective diameter in a retrieved pipeline (Milind Deo et al., 2010).

Conventional Method of Wax Deposition Control

The technology evaluation report by Milind Deo et al [2010], considered these methods under three broad categories, namely:

- Mechanical methods.
- Chemical/biodegradation methods.
- Thermal methods.

The mechanical method includes such activities as; internal coatings, cold flow, pigging, etc.

Internal coatings are used to prevent wax crystals and particles from precipitating onto the internal walls of the pipelines. Common coatings are phenolics, epoxies, phenolic-epoxies, nylon, Teflon, etc. According to the technology evaluation report by Millind Deo et al [2010], the chemical nature of the coatings should work to prevent wax surface molecular interaction. Many studies have shown that the insulator nature of some of these coatings does more to prevent deposition than its chemical nature (Efnor 1996, DEEPSTAR 3205.2 and HSU. 1997, DEEPSTAR 3205.3). According to the study by HSU 1997, nylon coatings seem to decrease wax deposition at high flow rates and temperatures close to the cloud point temperature.

Cold flow technology takes advantage of the fact that while there may be solid crystals present in the fluid being transported, the driving force for their precipitation either can be minimized or eliminated (Milind Deo et al, RPSEA 1201 controlling wax deposition in the presence of hydrates, a technology evaluation report). Thus, cold flow pre-cools crude oil before it enters the flow line. The crude oil is cooled to temperatures equal to the ambient temperature in a mechanical device. This ambient temperature is usually less than the wax appearance temperature for the crude oil system. This cooling causes the suspended solids in the crude oil to come out of the solution. The solids formed are then transported along with the crude oil system as sludge.

Pigging refers to the passing of specially engineered solids through a pipeline in order to clean or inspect the pipelines. It is one of the oldest means of removing wax deposits in the oil industry. A force balance for scrapper pigs has been developed in the literatures (Milind Deo et al, RPSEA 1201 technology evaluation report). It is giving as

$$F_t = F_b + F_s + F_{ws}$$

Where,

F_t = Total Force to move Pig (Static force for constant velocity, no acceleration).

F_b = Baseline force (frictional) between Pig and Pipe Wall

F_s = Breaking force of wax (gel strength?)

F_{ws} = Frictional force between Wax Plug and Wax Deposits.

Modern pigging designs incorporate the latest technology for dealing with traditional concerns such as multiple diameter lines, subsea lurching, and flow-by-pass.

Another method of wax control proposed in the literature is the *sonic method*. It is not very common. The concept is to position an ultrasonic generating device adjacent to the production tubing to disintegrate wax formed at the wall (Fowler et al 2007). Ultrasonic waves also increase the temperature of the flowing fluid. However, according to Milind Deo et al technology evaluation report, the scientific basis of these methods is not yet established.

Certain chemicals that are capable of decreasing the pour point temperature serve as useful wax deposition inhibitors. They can be used as *chemical inhibitors* in controlling wax deposition. Milind Deo et al [2010] reported on the effect of wax crystal modifiers on WAT, pour point, and viscosity. They reported that there was significant viscosity reduction and slight decrease in WAT with the use of inhibitors like *polyalkyl methacrylate* etc. However, these wax inhibitors have limited application and only decreases the rate of wax deposition. In offshore platforms and in arctic regions of the world with very low ambient temperature, their effect is not very pronounced. Moreover, the upfront cost of preparing and deploying sufficient volume of these chemicals is quite prohibitive.

Another method of wax control in the literature is the *biodegradation method*. It is true that the application of biotechnology in the microbial recovery of waxy crude has being well researched. However, less attention has been paid to the application of these methods to pipeline remediation. This might be due to the fact that microbial processes are typically slower than what might be required for faster pipeline operations. Hans Kristian Kotler et al [2007] recently reported wax control by bio-catalytic degradation of high paraffinic crude. They isolated a strain of *Acinobacter* and studied the degradation of long chain alkanes. The applicability of the method under flowing conditions, and in other environments will have to be investigated.

Thermal method is another very promising wax control technology that is been embraced today. The objective here is to supply heat continuously to the flowing crude oil system. One method of doing this is by circulating heated glycol-water mixture. This ensures that the crude oil temperature never falls below the wax appearance temperature. Alternatively, the heat can be supplied by direct electric heating. This is known as *electrical heat tracing*. This process utilizes the heating effect of electric current as it flows through a material of high resistivity. This method is also very important as it minimizes or eliminates hydrate formation. Currently this technology has been used in the Gulf of Mexico. The setbacks are its prohibitive cost and suitability for long distance flow lines and tiebacks.

Evolution of Wax Prediction Model

With the development of different technologies for wax prevention and control, it became evident that for us to effectively control or mitigate wax production, we need to understand fully the process of wax deposition. Hence, efforts to understand the phenomenon of wax precipitation and deposition were made. Attempts were made to develop models that can predict when, where and how wax will deposit. A number of such models are in the literatures. Let us look at some of them.

Won [1988] presented his first model for predicting wax appearance temperature. Using the Suave Redlich-Kwong (SRK) equation of state and employing a modified regular solution approach for solid-liquid equilibrium calculations (SLE). Activity coefficients were calculated using solubility parameters of individual components of hydrocarbon fluid. The critical

temperature, critical pressure and eccentric factors were estimated using correlations suggested by Spencer and Daubert, Lydersen and Lee-kesler respectively. The fusion temperature and heat of fusion were correlated to molecular weight using experimental data predominantly for pure n-paraffin with odd carbon numbers.

In 1986, Won modified his first model by using an approach that combined the modified regular solution approach with the equation of Flory-Huggins for calculating activity coefficients in the liquid phase. The wax models proposed by Won was validated against cloud point temperatures measured for synthetic fuels, diesel fuels, and North Sea gas condensates, Many researchers have adopted Won's model sometimes without any modification, when developing their own model .

However, as pointed out by H.Y. Ji et al, there are several shortcomings in the model proposed by Won that limits its reliability for predicting wax phase boundaries. First, two different approaches are applied to the liquid phase for VLE and SLE; an EOS is used for VLE, while an activity coefficient is used for SLE. This leads to inconsistencies in the description of the liquid phase and very often results in convergence issues. Secondly, the modified regular solution approach used for describing wax solid does not vary greatly from the ideal solid solution approach due to the similarity of the solubility parameter for n-paraffin. Both approaches lead to over estimation of the temperature of the wax phase boundary (Wax appearance temperature). Moreover, the model cannot provide reliable prediction of WAT at higher pressures. Finally, Won's model over estimates the amount of wax deposited. This is because it assigns the melting point of n-paraffin to all the hydrocarbon pseudo-components.

Hansen et al [1988] presented a wax model that uses the Suave-Redlich-Kwong (SRK) equation of state for Vapor Liquid equilibrium calculations. They applied the cloud point temperature for 13 North Sea crude oils. It is not surprising that the predicted WAT agreed with the experimentally measured WAT data for the same North Sea crude oils. Hansen's model had similar limitations as Won's model; Moreover, the polymer solution approach used by Hansen et al leads to activity coefficient in the order of 10^{-10} , which is not obtainable in reality.

Svendsen developed a mathematical model for prediction of wax deposition in both open and close pipeline systems by using a combination of analytical and numerical models. The model predicts that wax deposition can be considerably reduced when the wall temperature is below wax appearance point, provided that the liquid/solid phase transition expressed by the change in moles of liquid with temperature is small at the wall temperature. If, in addition, the coefficient of thermal expansion is sufficiently large, some components may separate and move in opposite radial direction at temperature below wax appearance temperature. Particle transport and sloughing were not considered.

Pedersen et al [1991] presented a wax model based on modifications to Won's approach. He applied a modified regular solution approach to both liquid and solid phases. He was able to distinguish between the wax-forming component and the non-wax forming component of a hydrocarbon system. Fusion properties and heat capacities were tuned to fit measured wax precipitation data for North Sea oils. The model was validated using experimental WAT data for the North Sea oils.

In 1995, Pedersen further modified this model, employing a cubic equation of state for consistency in description of the liquid phase for VLE and SLE calculations; the Ideal solid

solution approach was applied to the solid phase. Fusion properties were calculated using correlations suggested by Won. The problem however, with Pedersen's model is that it uses unreliable values for fusion properties and heat capacity. In addition, the approaches used to describe wax solids in the models led to an over estimation of wax phase boundary temperatures. The greatest shortcoming of this model is that it assumes ideal behavior for the solid phase.

Coutinho et al [1995] evaluated several approaches for calculating activity coefficients in SLE, including the Flory-Huggins Universal Functional Group Activity Coefficient (UNIFAC), Flory free-volume and entropic free volume. Consequently, in 1998, Coutinho presented a wax thermodynamic model that used a combined UNIFAC and Flory free-volume approach to describe the liquid phase, with the universal quasi-chemical (UNIQUAC) equation being used to describe wax solids. Coutinho's model was validated using experimental data for the amount and composition of wax precipitated for mixtures.

In 2000, Paul et al modified Coutinho's model. They used suave-Redlick-kwong equation of state for the description of the vapor and liquid phases. Critical parameters were obtained using correlations proposed by Twu. The Poynting correction term was used to extend the model to high-pressure conditions. Partial molar volumes required for calculating the Poyntin correction terms were estimated in accordance with crystallographic studies of n-paraffin solids. This model was validated using experimental WDT data for n-paraffin mixtures.

Modified Won's Model

The major criticism against Won's model is that it over predicts the amount of wax deposited at a given temperature. This is because it assumes that all the crude oil components are capable of forming wax. In reality, this is not the case. It is only the C_{7+} fractions that are capable of forming wax. Pedersen corrected for this by dividing the crude oil component into the wax forming and the non wax forming component. Pedersen also introduced new fusion parameters. Pedersen's model is not as accurate when predicting the wax appearance temperature of crude oil component. However, it does not over predict the amount of wax deposited. Hence, in order to be able to predict the WAT of a crude oil sample with the accuracy inherent in Won's model while not over predicting the amount of wax deposited, Won's model is corrected to account for the fact that only the C_{7+} fraction are capable of forming wax. Let us take a look at the basis for this model.

Consider a system undergoing equilibrium flash vaporization.

Carrying out material balance on the system,

$$F = L + S \text{ --- (1)}$$

Applying material balance to a particular component i , we have;

$$F \cdot z_i = L \cdot x_i + S \cdot s_i \text{ --- (2)}$$

Since the solid and the liquid exiting the flash vessel are in equilibrium, we have that

$$s_i = K_i^{SL} \cdot x_i \text{ --- (3)}$$

Where K_i^{SL} is the equilibrium ratio of mole fraction of component i in the solid and liquid phases at a given temperature and pressure.

Combining equations 1 to 3, we have

$$F \cdot z_i = (F - S) \cdot x_i + S \cdot K_i^{SL} \cdot x_i \quad \text{--- (4)}$$

Simplifying, we have

$$x_i = \frac{z_i}{1 + \frac{S}{F}(K_i^{SL} - 1)} \quad \text{--- (5)}$$

And

$$s_i = \frac{K_i^{SL} \cdot z_i}{1 + \frac{S}{F}(K_i^{SL} - 1)} \quad \text{--- (6)}$$

Since $\sum(s_i - x_i) = 0$, we have that

$$f^{(S/F)} = \sum \frac{(K_i^{SL} - 1) \cdot z_i}{1 + \frac{S}{F}(K_i^{SL} - 1)} = 0 \quad \text{--- (7)}$$

Equation (7) above is known as the Rachford-Rice equation. In performing flash calculation, the feed moles F , feed composition z_i , Pressure P , and Temperature T are known. It is evident that if the equilibrium constant K_i^{SL} is known, we can find the other unknown parameters. Thus, the focus of the WAT prediction model is to develop an equation for calculating K_i^{SL} .

According to Won's model, at equilibrium,

$$f_i^l = f_i^s \quad \text{--- (8)}$$

Where f_i^l = liquid phase fugacity of component i

f_i^s = solid phase fugacity of component i

But

$$f_i^l = \gamma_i^l x_i f_i^{ol} \quad \text{--- (9)}$$

Where γ_i^l is the fugacity coefficient of component i in the liquid phase.

x_i = mole fraction of component i in liquid phase.

Similarly,

$$f_i^s = \gamma_i^s s_i f_i^{os} \quad \text{--- (10)}$$

Where γ_i^s is the solid phase activity coefficient of component i .

s_i = solid phase mole fraction of component i .

Combining equation (9) and (10) we have;

$$k_i^{sl} = \frac{s_i}{x_i} = \frac{\gamma_i^l f_i^{ol}}{\gamma_i^s f_i^{os}} \quad \text{--- (11)}$$

Since there are no existing equations to describe accurately the volumetric behavior of a solid, we can find the ratio of f_i^{ol} to f_i^{os} using the following equation.

$$\ln \frac{f_i^{ol}}{f_i^{os}} = \left[\frac{\Delta H_i^f}{RT} \left(I - \frac{T}{T_f} \right) + \frac{\Delta G}{R} \left(I - \frac{T^f}{T} + \ln \frac{T^f}{T} \right) + \int_0^p \frac{\Delta v}{RT} dp \right] \dots (12)$$

Where T^f , ΔH_i^f , ΔC_p , and Δv are fusion temperatures, heat of fusion, heat capacity change during fusion, and volume change during fusion respectively; P and T are pressure and temperature respectively at which flashing is carried out.

Therefore equation (11) becomes,

$$k_i^{sl} = \frac{S_i}{x_i} = \left(\frac{\gamma_i^l}{\gamma_i^s} \right) \exp \left[\frac{\Delta H_i^f}{RT} \left(I - \frac{T}{T^f} \right) + \frac{\Delta C_p}{R} \left(I - \frac{T^f}{T} + \ln \frac{T^f}{T} \right) + \int_0^p \frac{\Delta v}{RT} dp \right] \dots \dots \dots (13)$$

Where

$$\Delta C_p = C_{pi}^l - C_{pi}^s \dots \dots \dots (14)$$

Fusion Parameters

The correlation proposed by Won is used to calculate fusion parameters. They are given as;

$$\Delta H_i^f = 0.1426 MW_i T_i^f \dots \dots \dots (15)$$

$$\text{Where } T_i^f = 374.5 + 0.02617x MW_i - 20172 / MW_i \dots \dots \dots (16)$$

And MW_i = molecular weight of component i , and T^f is the fusion temperature. The molecular volume of a component in liquid phase is obtained from Won (1986) as:

$$v_i^l = \frac{MW_i}{d_{25}^l} \dots \dots \dots (17)$$

$$\text{Where } d_{25}^l = 0.8155 + 0.6272x10^{-4} - 13.06 / MW_i \dots \dots \dots (18)$$

Therefore, the molar volume of component i is given as;

$$v_i^s = 0.9x v_i^l \dots \dots \dots (19)$$

Since the solid phase is anon-ideal mixture, this means that the ratio of the activity coefficients cannot be equal to

$$\frac{\gamma_i^l}{\gamma_i^s} \neq 1 \dots \dots \dots (20)$$

Therefore, we use the regular solution theory by Florry Huggins to estimate the ratio of activity coefficients, thus;

$$\ln \gamma_i = \left(\frac{\bar{\delta} - \delta_i}{RT} \right)^2 \dots \dots \dots (21)$$

Where $\bar{\delta}_i$ = solubility parameter for component i and $\bar{\delta}$ = average solubility parameter of the mixture.

$$\bar{\delta} = \sum \varphi_i s_i \dots \dots \dots (22)$$

Where φ_i = volume fraction of component i , it can be obtained for both liquid and solid phases as shown below.

$$\varphi_i^l = \frac{x_i v_i}{\sum x_i v_i} \dots \dots \dots (23)$$

And

$$\varphi_i^s = \frac{s_i v_i}{\sum s_i v_i} \dots \dots \dots (24)$$

From Pedersen correlations, we have that

$$\delta_i^l = 7.41 + 0.5914 (\ln C_n - \ln 7) \dots \dots (25)$$

$$\delta_i^s = 8.50 + 0.763 (\ln C_n - \ln 7) \dots \dots (26)$$

$$\frac{y_i^l}{y_i^s} = \exp \left[\frac{v_i}{RT} \left((\bar{\delta} - \delta_i)_l^2 - (\bar{\delta} - \delta_i)_s^2 \right) \right] \dots \dots \dots (27)$$

Therefore, equation (11) becomes, after simplification;

$$k_i^{sl} = \frac{s_i}{x} = \exp \left[\frac{\Delta H_i^f}{RT} \left(1 - \frac{T}{T^f} \right) + \frac{v_i}{RT} \left((\bar{\delta} - \delta_i)_l^2 - (\bar{\delta} - \delta_i)_s^2 \right) + \Delta v^f \left(\frac{p - p_{ref}}{RT} \right) \right] \dots (28)$$

Considering the fact that not all the crude oil component contributes to wax formation as pointed out by Pedersen, the mole fraction of the wax forming component Z_i^s , is given as

$$Z_i^s = Z_i^{old} \left[1 - (A + B \cdot M_i) \cdot \left(\frac{\rho_i - \rho_i^p}{\rho_i} \right)^C \right] \dots (29)$$

Where

- Z_i^{old} = Total mole fraction of feed.
- Z_i^s = Mole fraction of potentially wax forming component.
- M_i = the molecular weight of pseudo-component i ,
- Z_i^s is related to Z_i^{old} as shown above;
- ρ_i = Density of the pseudo component at standard conditions,
- ρ_i^p can be obtained from,

$$\rho_i^p = 0.3915 + 0.0675 \ln M_i \dots \dots \dots (30)$$

Also,

$$Z_i^{no-s} = Z_i^{old} - Z_i^s \dots \dots \dots (31)$$

Where Z_i^{old} is the mole fraction of the non-wax-forming component. The values of A, B, and C is gotten by tuning the parameters with experimental data. Thus, all the C_{7+} fractions are split into two: the wax forming parts and the non wax forming parts. The graph below compares the modified model with Won's model and experimental data.

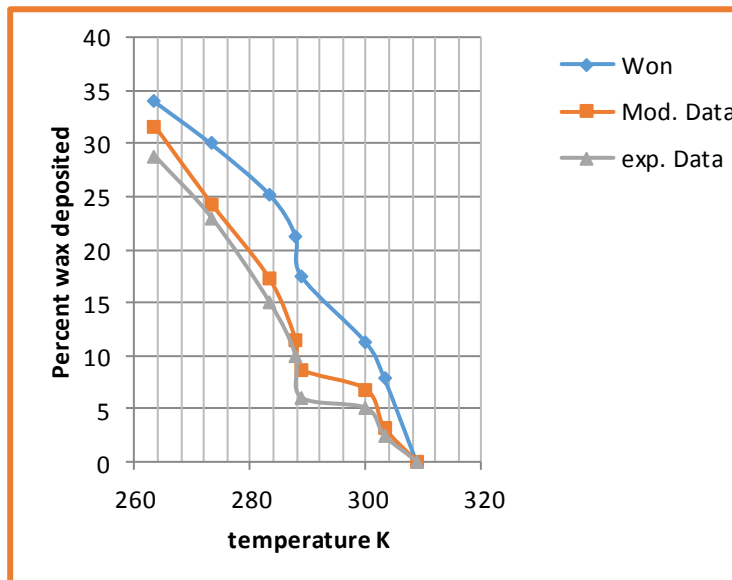


Figure 1.4: Graph showing accuracy of new model, Dauphin et al, 1999

From the graph above, it is evident that the modified model performs significantly better than Won's model when it comes to predicting the amount of wax precipitated at temperatures below

WAT. This is expected because it recognizes that only a fraction of the C_{7+} components actually contributes to wax formation. It also predicts the WAT of the given crude oil system as accurate as Won's model.

Similarly, the second graph confirms the validity of the improved model. The modified model predicts the WAT of the given crude oil sample with a lot more accuracy than the often used Won's model.

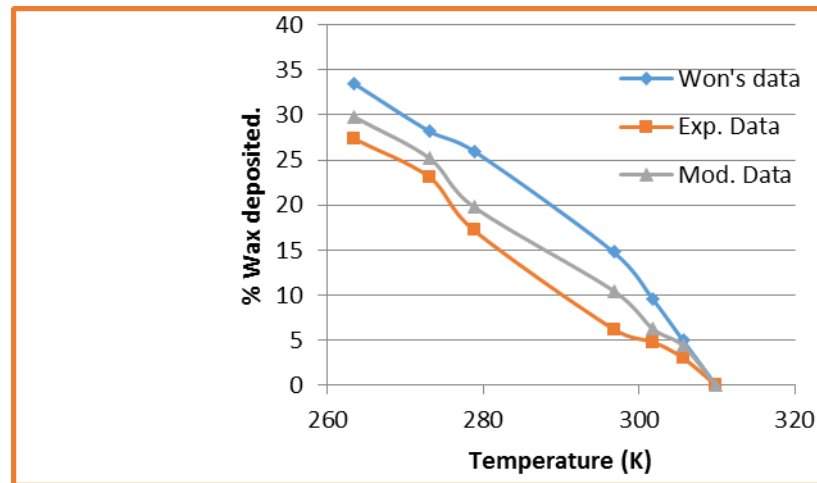


Figure 2.5: Graph showing accuracy of new model, Dauphin et al, 1999

Model Application

A number of factors affect wax deposition. Among these factors are; temperature, pressure, crude oil composition, pipe surface roughness, etc. Of all these factors, temperature is the most important. This is because no wax will be deposited no matter the condition, so long as the crude oil temperature is above the wax appearance temperature. Other factors will lead to wax formation only when the crude oil solubility limit (WAT) is reached.

A recent study carried out by Kellogg et al (as reported by Milind Deo et al), ranked 10 benchmark wax mitigation technology. In it, active heating, which also includes electrical heat tracing, was co-ranked in third place with the coiled tubing technology. The major criticisms against electrical heat tracing were concerns over its long distance viability and high prohibitive cost of implementation. The ranking is shown in table 1.1. However, due to the depletion of conventional onshore fields and the rising cost of pigging in deep offshore platforms, there is an urgent need for a more proactive method of wax control. This need becomes more urgent if you consider the fact that major oil findings have been made in very cold regions of the world, such as the Alaska North Slope (ANS) field.

Due to the very low ambient temperatures in these places, wax is more readily deposited. This is because the rate of wax deposition is proportional to the temperature difference between the flowing crude oil in the pipeline and the ambient temperature. Considering the fact that the electrical heat tracing method which utilizes the heating effect of electric current is a proactive method, it becomes obvious that it is the most practical alternative to pigging. However, to make this method more economically attractive, a little modification needs to be made. Here comes the *modified electrical heat tracing technology*.

Table 1.1; Table showing benchmark wax mitigation technology, Milind Deo et al.

Technology	Cold flow applicability	Scientific basis	Long distance viability	Range of applicability	cost	Overall rank	comment
Pigging	10	10	9	10	5	8.8	A “must use” mitigation technology. Cold flow will be implemented with pigging back up options.
Cold seeding	9	8	7	5	7	7.2	Good scientific bases and possibility of long distance implementation. Range of applicability needs testing and cost could be higher than the benchmark.
Coiled tubing	7	9	3	8	7	6.8	Usually combined with advanced pigging. May be less applicable over long distance.
Active heating	9	10	5	7	3	6.8	Applicable technology. Sound technical and scientific basis. Concerns are long distance viability and cost.
Chemical inhibition	5	6	5	5	5	5.2	Case specific and can be expensive.
Internal coatings	3	2	9	1	3	3.6	Viable over long distance. Weak scientific basis.
Sonic methods	1	2	7	1	3	2.8	Not enough data to indicate proof of concept.
biodegradation	2	1	1	1	5	2	Shown not to be applicable in deep star work.
Magnetic methods	1	3	1	1	3	1.8	Not enough proof of viability.
Micro wave methods	3	3	1	1	1	1.8	No proof. Even if fundamentally applicable, difficult to implement.

The modified heat tracing technology seeks to lower the cost of its implementation by reducing considerably the total length of the flow line heat traced, thereby improving its long distance viability. How is this achieved?

Having predicted the WAT of a given crude oil system, the temperature profile of the flowing crude oil in the flow line is then modeled. With this model, we can predict exactly where and when wax will begin to precipitate in a given flow line. Thus, instead of heat tracing continuously throughout the length of the flow line, the regions where the wax will be formed is heat traced, thus allowing the crude oil temperature to be raised above its WAT. This implies discrete heat tracing.

Conclusion

With the application of this technology, electrical heat tracing of flow lines will become the most effective method of wax mitigation. The down time incurred while trying to pig flow lines will be eliminated. It will represent a huge step towards solving flow assurance problems. Hydrates will no longer be formed as the flow line temperature will be above the hydrate formation temperature. Moreover, the power requirement for transporting fluids in the flow line will reduce tremendously, as it is an inverse function of the fluid's viscosity. Also, due to the heating, the API value of the crude is expected to improve, as the heavier components will become partially cracked. Thus, all this benefits puts the modified heat tracing technology in good stead to become the industry standard for wax formation prevention and control.

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