

Need of Flow Assurance for Crude Oil Pipelines: A Review

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Abstract– Flow assurance involves ensuring fluid flow in well, flowline and trunkline. Transportation of heavy/waxy crude oils with high viscosity makes flow through pipelines difficult and challenging. Furthermore, waxy oil transportation from the wellhead to the refinery gate is becoming important as their production has to be ensured through flow assurance. Huge amount of capital is spent annually by the petroleum companies for the prevention and removal of wax in production and transportation lines. It has been established that n-paraffin's are predominantly responsible for this problem. These solid particles deposit in production tubing, pipelines, processing equipments and eventually cause plugging in the operations. Reduction in the cost of production operations can be achieved through accurate prediction of Wax Appearance Temperature (WAT) and the amount of wax likely to be deposited under given conditions. Apart from the conventional approaches used till the 1990's, in last two decades many alternative methods have been developed and extensive work has been carried out in this area due to its high impact on petroleum industry. The available approaches present a diversified picture and their validation can be analyzed by actual field data. The paper addresses flow assurance aspects related to crude oil pipelines & reviews its chronological status in the petroleum industry.

Keywords– Flow Assurance, Wax Deposition and Thermodynamic Model

I. INTRODUCTION

The term Flow Assurance was devised by Petrobras in the early 1990s meaning "Guarantee of Flow". The safe and efficient delivery of hydrocarbons from the well to the collection facilities is the most important component of Flow Assurance. Oil companies are developing unconventional oil fields with complex fluid properties with the decline in conventional oil reserves, thus flow assurance plays very important role in the oil and gas industry.

While flowing through a long pipeline, it is important to take an account of viscosity, acidity and salt content for field operations. All these factors can affect pipeline capacity. The process of ensuring a constant flow of oil despite different issues which can cause flow obstacles is known as Flow Assurance. Although Flow Assurance consists of a spectrum of issues, four main issues are: corrosion, salts, asphaltenes and waxes. (Hussain et al., 1999)

Alongwith the flowline Sulfate Reducing Bacteria (SRB), sour gas (H_2S , also from SRB's), and seawater (in oceanic wells) can and do find their way into the lines, and once there

they can cause serious issues. Acidification of the oil due to the presence of sour gas may corrode the pipeline walls, these being made of stainless steel (very resistant to oxidation, but weak to acidity), corroded pipelines can develop complete perforations, through which oil can be lost and may lead to environmental problems. Salt from seawater can also cause serious flow issues by crystallizing on the walls and reducing the flow. These salt deposits are hard and difficult to break without chemical intervention, but usually the formation of such deposits can plug the pipeline. Asphaltenes are the complex carbon-based molecules characterized by groups of interconnected aromatic rings. They can cause flow problems, particularly in the wellhead itself as well as in the refinery lines. Asphaltene solubility and precipitation needs considerable attention.

During flow through pipeline, wax may be deposited on pipe walls. A thermal gradient between the outside ambient conditions and the internal oil flow must exist for flow deposition. The internal wall temperature due to the gradient must be below the initial wax appearance temperature. In addition, internal shear forces in the flow must be low enough to allow crystal growth. Wax deposits, can grow and restrict flow. While it is rare for deposition to completely shut down a pipeline, the loss in production capacity is a major concern during waxy crude oil transportation through pipelines.

Flow assurance is an important area for multiphase flow of oil, gas and water to minimize financial loss for the petroleum industry. As multiphase meters are dependent on accurate data for fluid properties an incorrect fluid property data or change in composition/salinity can give an inaccurate flow measurement and finally lead to financial losses.

Recently, methods of transporting multi-phase fluids through pipelines and wells have advanced rapidly. Multi-phase flow plays an important role in the petroleum industry. The latest advancements have made it possible to transport un-separated gas-oil-water mixtures over quite long distances. This has an enormous economic impact on offshore and onshore developments.

II. BACKGROUND OF FLOW ASSURANCE

In 1927 paraffins were reported as nuisance to the upstream industry due to their precipitation and accumulation in the wall of the well, in the oil string and on the face and in the pores of the sand, resulting in congealing of oil in the

transportation lines and in tank bottoms (Reistle and Laramie, 1927).

During 1920-1930, most of the developments were in thermal methods for the solution to paraffin problems. These treatment methods normally consisted of minimizing radiation heat losses and addition of external heat to the system. Insulation of flow lines and maintaining a higher pressure in the flow lines that minimized cooling through dissolved gas expansion were two examples of minimizing radiation losses. Methods such as steaming the flow lines, installing bottom hole heaters and circulation of hot oil and hot water are examples of the application of heat in an effort to melt or increase the solubility of the deposit. However, both mechanical and thermal methods did not modify the primary oil wettability of the surfaces of pipelines and, therefore, could not prevent further deposition of waxes. As a result, the frequencies of such measures generally required to be high.

The mechanical methods used scrappers, cutters, pigs etc. and were relatively economical but not entirely efficient. Running a scrapper that mechanically cuts the deposit from the tubing was used widely and pigging of pipelines was also frequently used. The problems associated with these methods were the chances of perforation plugging and an increase in oil-in-water emulsion stability.

Till 1966 it was understood that the rate of deposition due to the precipitation of wax could be controlled with addition of additives (Shock, et al., 1955, Jorda, 1966). Tests of various plastic coatings indicated that most smooth, non-paraffinic plastics were capable of reducing paraffin deposition in oil wells, but flexible, highly polar, non-paraffinic plastics were more suitable for providing long term resistance to paraffin deposition in oil wells if the flow stream contained abrasive materials. Paraffin deposition was studied in the laboratory under simulated conditions in well tubing and it was proposed that paraffin deposits were initiated by the precipitation of paraffin directly on or adjacent to the pipe wall and grown by diffusion of paraffin from solution to the deposit (Hunt, 1962)

During 1950-1970 developments in laboratory scale technology were carried out to identify and categorize wax as well as simulating the conditions of paraffin deposition in the laboratory. Prediction of wax deposition behavior in tubing /trunk line was also simulated in order to understand the wax formation mechanism.

The wax deposition mechanism was properly understood during the above period, which served as the basis for research & development during 1980s.

The chemical control methods may be classified as:

- i) Those in which a solvent is used to dissolve the deposit once it has formed
- ii) Those which inhibit wax crystal growth or inhibit its adherence to the surface wells.

The solvents may be used alone such as xylene or in combination with more than one solvent of a mixed system consisting of xylene, toluene and naphthalene to enhance the dissolving capacity of the solvent system. The use of solvents is generally more effective than mechanical or thermal methods. However, solvents are usually very inflammable, incompatible with demulsifying chemicals, do not modify the

surface oil wettability to prevent redeposition and may be very costly.

Surfactants may also be used to inhibit paraffin deposition. The surfactants adsorbing on the surfaces of the tubings and flowlines form a film acting as a barrier and preventing the deposition. Although the method may be effective, it should be applied only after the deposits have been removed. Another problem of surfactant application is the influence of surfactant on the oil-in-water emulsion stability.

Rose and Marsden (1970) made an attempt to study the nature of low temperature flow of Prudhoe Bay crude oil through pipeline (a long tubular conduit or series of pipes, often underground, with pumps and valves for flow control, used to transport crude oil, natural gas, water, etc.) and its emulsions with synthetic brine. They found a significant lowering of apparent viscosity and pressure drop through the flow resistance due to the use of oil-water emulsions. Van Engelen et al. (1979) observed that properties such as pour point, plastic viscosity and yield value measurements are quick and helpful methods for the initial screening of fluidity improvers. This case study verified the validity and accuracy of laboratory studies conducted on various additives for determining the restartability of a submarine pipeline.

Paraffin deposition can be prevented or greatly retarded by using chemical surfactants called "dispersants" (Meclaffin and whitfill, 1984). The choice of using batch or continuous treatment is governed by the type and number of wells requiring treatment. Woo, et al., (1984) discussed the use of a blend of crystal modifiers in a controlled-release matrix form and a commercially available ethylene-vinyl acetate copolymer solid. Among the chemicals used, crystal modifiers and paraffin/wax dispersants are quite common. The paraffin crystal modifiers change the crystallization behavior of waxes. The effectiveness of the crystal modifier depends, to a large extent, on the type of aggregate-forming waxes that are present in the oil. Thus, the choice of a crystal modifier is key to success for the treatment. They perform well in water free or low-water content crude oil. These polymers co-crystallize with paraffin crystals and thus paraffin crystals are kept in a dispersed position in the crude oil. In this way, the formation of a three dimensional network takes place at lower temperatures which results in a substantial reduction in the viscosity and pour point of the crude oil (Dobbs, J.B., 1999)

Ronningsen, et al., (1991) discussed three different techniques for determination of Wax Precipitation Temperature (WPT), namely Polarization Microscopy, Differential Scanning Calorimetry (DSC) and Viscometry. The results obtained by these methods were compared and it emerged that Microscopy invariably gave the highest WPTs and probably the most relevant values for predicting the onset of wax deposition on cold surfaces. Thermodynamic paraffin model and the complementary laboratory test methods were described by Erickson, et al., (1993). The method consisting of a periodical application of detergent designed to remove the deposit and simultaneously destroy the water-in-oil emulsion were suggested by Bernadiner (1993). Chanda et al. (1998) used Poly Behenyl Acrylate (PBA) with a range of molecular weights and their efficacy as Flow Improver (FI)/Pour Point Depressant (PPD) were evaluated.

Karan et al (2000) used a new High-Pressure Microscope (HPM) which was developed for visual detection of organic solids precipitation during isobaric cooling, isothermal depressurization and isothermal-isobaric titration tests. The microscope was rated to 138 MPa (20,000 psi) and 200°C.

During the decade of 1991-2000, laboratory developments along with modern chemical advancements were noticed. It was established that selection of chemical combinations was well specific and based upon individual experience. Also many new solvents and additives were discovered which were case specific.

In the last decade Flow Assurance has emerged as a major technical discipline and has gained attention due to its impact in the petroleum industry. It has given rise to an inter disciplinary research wherein along with the development in laboratory and use of various chemicals, emphasis on modeling and simulating the pipeline under various conditions has been studied at large. This has led to the development of real time data monitoring software and Flow Assurance Advisory systems. These systems rely on good model predictions and available sensor readings in the production system. These software are still growing and various rigorous and robust models for flow assurance issues have been customized based on specific field characteristics (Kondapi and Moe, 2013)

The use of unconventional energy in the upstream and midstream industry is now possible. A Dynamic Simulator has been developed to evaluate the pressure drop and temperature profile of a solar heated pipeline which can compare it with a bare pipeline under average sunshine conditions. This technology is an innovative and economically attractive alternative to the conventional electric or steam heat tracing of pipelines or utilization of Drag Reducing Agents (DRA's) or pour point depressants. Depending upon process requirements, this technology is specifically suited for tropical and mid-latitudes. This technology is also suitable for vessels (Lasich and Kaila, 2001)

Since conventional methods like thermal application and chemical injection are turning out to be expensive, an alternative approach has now been developed. These method use application of magnetic, electric and piezoelectric effect on crude oil to improve its rheological properties.

Chow, et al. (1998) made a successful use of Magnetic Fluid Conditioning (MFC) technology to reduce the viscosity of crude oil. Their results identified state of wax saturation as an important factor for undergoing magnetic treatment. Tung, et al., (2001) found that the effects of magnetic treatment were strongly depending on temperature, magnetic intensity and time of exposition.

Tao and Xu (2006) studied the application of electric field pulse and discovered significant decrease in viscosity of paraffin-base crude oil. Although the viscosity reduction is not permanent, it would last several hours.

Sulaiman et al. (2011) developed a tool that could control wax deposition using of piezoelectric effect. The mechanism of semiprecious metals (Zinc, Cobalt and Lead) quartz and were studied and found to be successful in decreasing / eliminating wax deposit in the production system through the generation of piezoelectric reaction.

Although, these technologies are still in their embryonic stage, they look quite promising to face flow assurance challenges.

III. WAX DEPOSITION MECHANISM

When a waxy crude oil gets cooled, i.e., during its flow through a pipeline, the crude oil temperature reaches the ambient temperature. At temperature below the cloud point / Wax Appearance Point (WAP), paraffin starts to crystallize. The wax precipitated from oil mixtures primarily consists of C₁₈ to C₃₆ (paraffin waxes) or C₃₀ to C₆₀ (microcrystalline waxes), both made up of aligned paraffinic and naphthenic molecules. Paraffin waxes are also called macrocrystalline waxes. The wax deposition in actual pipelines can take place at higher temperatures than those actually measured in the laboratory because in a pipeline, the roughness of the wall and/or presence of nucleation sites, such as solids, corrosion products etc. play great role for depositing wax from under saturated fluids. The n-paraffins give rise to clearly defined needle shaped crystals and are the major constituent of macro crystalline waxes. The branched chain paraffins form the principal portion of microcrystalline waxes. The long straight chain naphthenic and aromatic type paraffins also contribute to microcrystalline waxes and also have a marked impact upon the kind of crystal growth of macrocrystalline waxes. The deposition of macro crystalline waxes generally lead to paraffin problems in production and transportation of crude oil while microcrystalline waxes contribute most to tank bottom sludge (Ahmed and Raines, 1997).

The mechanism by which the wax deposition occurs is based on Molecular Diffusion and Shear Dispersion (Weingarten and Euchner, 1988). These mechanisms are the driving forces for the transportation of dissolved and/or precipitated paraffin to the pipeline wall. The gravity settling mechanism has also been identified as a wax deposition mechanism.

Molecular Diffusion Mechanism

The driving force for the Molecular Diffusion at any time is the concentration gradient (dc/dr) along the direction r, where c is the concentration of paraffin at a certain location from the pipeline wall at a lateral distance r. The mass flux of the dissolved wax molecule is:

$$n = - (D A d_c / d_r - (1)$$

Where,

D = diffusion coefficient

A = the cross section area

d_c / d_r = concentration gradient

The above equation can also be written as:

$$n = - (D A d_c / d_r - (2) \\ = - \rho D (d_c / dT) (dT / d_r)$$

Where, ρ = the density of the solid wax

dT / d_r = the temperature gradient

From the above equation, it is clear that the wax deposition rate reaches its maximum just below the differential temperature between oil and the pipe wall.

IV. WAX CRYSTALLIZATION

The solubility of paraffin waxes is very sensitive to changes in temperature. Paraffin waxes exist as soluble constituents of crude oil and under a state of equilibrium under most reservoir conditions. When this equilibrium is disturbed due to factors such as changes in temperature and pressure, the crystallization /precipitation of paraffin molecules may occur. Paraffin precipitation may also occur as a result of loss of volatile lighter fractions, which otherwise act as naturally occurring solvents. It has also been observed that there is an increase in wax crystallization temperature of crude after the loss of gases present in it due to decrease in pressure.

The reservoir temperatures generally exceed the critical temperatures of the lighter ends (methane, ethane etc.) and the non-hydrocarbon gases (nitrogen, carbon dioxide etc.). However, due to reservoir pressures, these components remain in solution in supercritical state. Supercritical light ends have a tendency to dissolve heavy ends. As a well starts flowing, a pressure gradient is established across the reservoir, well bore and wellhead. Due to decrease in pressure, the wax carrying capacity of super critical state decreases and this results in crystallization of waxes. The decrease in temperature of crude oil also enhances this phenomenon.

The solubility of paraffin in petroleum also decreases with increase in sum of tar and asphaltenes. However, it has also been observed that deposition of wax decreases as tar and asphaltene content increases. The reason for this may be that being in colloidal state; the asphaltenes prevent intensive crystallization, i.e., poor crystal growth and interlocking of paraffin from petroleum solution leading to poor depositional characteristics. The structures of the wax crystals formed in the crude oil varies a lot. It has been observed that both crystalline and amorphous waxes may be present in the crude oil. However, the crystalline behavior of the waxes can be altered by the medium in which the waxes are crystallizing, the condition under which the waxes are crystallizing and by the presence of certain colloidal materials in the crude oil. The presence of impurities like asphaltenes, resins and additives cause mal-crystallization of the waxes, i.e., it inhibits proper crystal formation.

V. FLOW ASSURANCE WITH SPECIAL REFERENCE TO WAX DEPOSITION

The crystallization of waxes in crude oil produces non-Newtonian flow characteristics including very high yield stresses that are time dependent upon the shear and temperature histories of the crude oil. The wax crystallization in crude generally leads to following three types of problems:

- high viscosity of the crude oil leading to pressure losses,
- high yield stress for restarting the flow in case of a pipeline shut down, and
- deposition of wax crystallites on various surfaces

High crude oil viscosity and wax deposition on pipe surfaces are major reasons for high pipeline pressures that also lead to turbulent flow behavior. The crystallization of wax increases the viscosity of the crude oil due to gel forming tendency of the wax crystallites (Calange, et al.,1997). This results in an increase in the viscosity of the crude oil and pressure losses leading to a reduction in the effective capacity of the pipeline. This would also lead to an increase in pumping pressures causing harmful effects on the pipeline and even stopping flow under extreme conditions. Another problem that is expected due to wax content of the crude oil is restarting flow in a line where static oil has been allowed to cool to temperatures below its pour point either due to a shut down or any other reason. In such cases a certain pressure known as 'restarting pressure' is required to break the gel and resume the flow. The 'restarting pressure' would primarily depend upon the wax characteristics in the oil as the strength of the gel depends upon the web of the wax crystals formed.

The wax crystal deposition at the surfaces of various components of production systems such as tubings, well heads, flow lines, tank bottoms, process equipments, sucker rods etc. lead to severe production upsets and this must be addressed at the earliest to avoid bigger losses in the crude oil production.

VI. FACTORS AFFECTING WAX DEPOSITION

The amount of wax deposition normally depends upon following three factors:

- Flow Rate
- Temperature Differential and Cooling Rate
- Surface Properties

Flow Rate: Slower the flow rate, higher the chances of wax deposition is a rule of thumb. In conditions of Laminar flow, the wax deposition may increase with the flow rate (Haq, M.A., 1981).

One probable reason for this may be availability of a greater number of particles for deposition at the surface. As the flow rate shifts to the turbulent regime, the wax deposition generally decreases with increase in turbulence and flow rate. Another feature of wax deposition at high flow rate may be that the deposits formed are harder and more compact due to the reason that only those wax crystals and crystal structures that are capable of firm attachment to the surface and having good cohesion among themselves form wax deposition. Wax deposition is found to be problematic in low flow rate wells like artificial lift wells. In such wells, the residence time of the oil in the tubing is more which leads to more heat loss and lower oil temperature resulting in more wax precipitation.

Temperature Differential and Cooling Rate: Temperature differential between the bulk of solution and the cold surface is another factor that affects wax deposition (Santosa, et al., 2004). Wax deposition increases with an increase in temperature difference. It has been observed that the temperature difference between the solution cloud point and depositing surface is more important than that between bulk solution and surface. Wax deposition would occur only when

surface temperature is below both the temperature of oil and the cloud point of the oil. Temperature differential also affect the composition of the deposited wax. Higher differential may result in simultaneous crystallization of both lower and higher melting point waxes forming a weak porous structure due to crystallization with cavities full of oil. At higher rate of cooling, the wax precipitates out in smaller crystals and large numbers of crystals are formed due to availability of a large number of crystallization sites. At lower rate of cooling, the more uniformly packed crystals are formed which possess a relatively small surface area and free energy.

Surface Properties: The conditions of the internal surfaces of the pipelines also affect wax deposition. The presence of adsorbed oil films on the metal surfaces reduces the adherence of paraffins to the surface. The wettability also affects wax deposition. The amount of wax deposited for a given temperature difference decreases with decreasing free surface energy. As the paraffin wax is deposited on a surface, it is held by adsorption forces. These adsorption forces are dependent upon the free surface energy possessed by both the paraffin and the surface. The paraffin deposition also increases with an increase in the surface roughness.

VII. THERMODYNAMIC MODELS FOR WAX PRECIPITATION

There are many models present in the literature that describe precipitation of wax from oil, and they can be broadly classified into two categories: 1) those which consider the solid phase as a single phase and 2) those which consider the wax phase as a mixture of multiple solid phases. Some models consider the solid phase as a mixture of multiple, independent pure solid phases. The rest of the models consider the solid phase as a single phase. The second category can be divided into two further subcategories. The first subcategory considers the solid phase as a non-ideal mixture, whereas the second subcategory considers the solid phase as an ideal mixture. Various models present in literature are divided into these categories.

A) Lira-Galeana Model (1966)

This model assumes that wax consists of multiple solid phases, and each solid phase is described as a pure component that does not mix with other solid phases. This considered a non-ideal solution, and its behavior is described by the Equation of State (EOS). This model is also known as the Multi-Solid model. The Lira-Galeana model assumes that a component may exist in pure solid form when the fugacity of the component in the liquid-phase mixture is equal to or greater than the solid state fugacity of the pure component.

The solid state fugacity of a pure component is determined by relating the chemical potential of a component in solid state with the chemical potential of a component in liquid state in sub cooled condition. The model actually fits the experimental data very well. However, Pedersen & Michelsen (1997) pointed out that the predictions from the model change when the plus-factor characterization procedure is changed.

B) Won's Model (Won 1986)

Won's model was the first one to consider the solid phase to be a non-ideal solution. Both liquid and solid phases were considered as non-ideal solutions, and non-ideality of both phases described by Regular Solution Theory. This model assumed that all components present can form wax. Pedersen et al. (1991) modified Won's original model by introducing a large number of tunable parameters to match the experimental data, but this makes the model also very calculation intensive.

C) Erickson's Model (Erickson et. al, 1993)

This model is a modification of Won's model, but considers the solid phase as an ideal solution. The activity coefficient of the solid phase is considered to be unity. But this model requires experimental determination of amounts of n-paraffinic, iso-paraffinic, and naphthenic parts of each component through mass spectroscopy. This determination involves huge efforts at the experimental stage and is rarely done. This model has not been used much.

D) Pedersen's Model and Its Modified Versions (Pedersen and Michelsen, 1997)

Pedersen and Michelsen developed a model in which it was assumed that only part of heavy hydrocarbon fractions can potentially enter into the wax phase. The authors developed a numerical scheme which allowed them to split each hydrocarbon fraction into wax-forming and non-wax-forming fractions. The authors assumed the solid phase to be an ideal solution in equilibrium with the liquid phase. The liquid phase is assumed to be a non-ideal solution and is described by any Equation of State (EOS).

Ronningsen et al. (1997) provided a modification of Pedersen's model, in which they introduced a term to account for the effect of pressure. This modified model is used in PVTsim®, which is a commercial PVT simulator for the prediction of wax deposition, and is used by many oil companies. Due to the use of EOS and tunable parameters, the modified model becomes very calculation intensive.

The next main category of thermodynamic models is one that considers the solid phase to be a non-ideal solution. Won's model, Pedersen's model, and Coutinho's model fall into this category.

E) Coutinho's Model

Coutinho's model considers solid and liquid phases to be non-ideal solutions. The non-ideality is described by activity coefficients. The activity coefficients are obtained by the predictive model with use of the predictive free energy model. Coutinho's model gives good predictions (Coutinho et al. 2001).

VIII. CONCLUSIONS

- i). Flow assurance in the recent past is progressing faster than the average applied engineering discipline as seen by recent developments.
- ii). Wax crystallization causes high viscosity, which leads to pressure losses & high yield stress for restartability.

These problems are governed by a very complex set of factors and can amount to heavy production and material losses if not taken care properly. Data from various laboratory studies, including studies simulating actual field conditions as closely as possible, can be used to evolve suitable solutions to a variety of field problems.

- iii). Number of methods has been used to predict paraffin problems, but their standardization still eludes the scientific community. The need of the hour is to standardize these methods for better technical/economic solutions.

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REFERENCES

- [1]. Ahmed, H. and Raines, M. A. Paraffin Deposition from Crude Oils: Comparison of Laboratory Results to Field Data. SPE 38776. Presented at 1997 SPE Annual Technical conference and Exhibition held in San Antonio, Texas, 5-8 October 1997.
- [2]. Bernadiner, M. G. Advanced asphaltene and paraffin control technology, SPE 25192. Presented at SPE International Symposium on Oilfield chemistry held in New Orleans, LA, USA, March 2-5, 1993.
- [3]. Calange, S., Ruffier-Meray, V., & Behar, E. Onset crystallization temperature and deposit amount for waxy crudes, SPE 37239. Presented at the 1007 SPE International symposium on oilfield chemistry held in Houston, Texas, 16-21 February, 1997.
- [4]. Chanda, D., Sarmah, R., Brothaku, R. A., Rao, K. V., Subrahmanyam, B., and Das H.C. Combined effect of asphaltenes and flow improver on the rheological behavior of Indian waxy crude oil, Fuel Vol 77 No.11, PP 1163-1167, 1998.
- [5]. Chow, R., Sawatzky R., Henry D., Babchin, A., Wang, Y., and Cherney, L. Precipitation of Wax from Crude Oil under the Influence of a Magnetic Field, 49th Annual Technical Meeting of the Petroleum Society in Calgary, Alberta, Canada, June 8-10, 1998.
- [6]. Coutinho, J.A.P., Pauly, J. and Daridon, J.L. A Thermodynamic Model to Predict Wax Formation in Petroleum Fluids, Braz. J. Chem. Eng., Vol 18, no. 4, 411-422. 2001.
- [7]. Dobbs, J.B., A Unique Method of Paraffin Control in Production Operations. SPE55647. Presented at 1999 SPE Rocky Mountain Regional meeting held in Gillette, Wyoming, 15-18 May 1999.
- [8]. Erickson, D. D., Niesen, V. G. and Brown, T. S. Thermodynamic Measurement and Prediction of Paraffin Precipitation in Crude Oil, SPE 26604, Presented at the 68th Annual Technical and conference and Exhibition at the society of petroleum Engineer held in Houston, Texas, 3-6 October 1993.
- [9]. Haq, M.A. Deposition of Paraffin Wax from Its Solutions with Hydrocarbons. SPE Paper No. 10541, 1981
- [10]. Hunt, E.B. Laboratory Study of Paraffin Deposition. JOPT1259, Trans., AIME, V. (225). Presented at SPE Production Research symposium held April 12-13, 1962 in Tulsa Oklahoma, USA.
- [11]. Hussain, M., Mansoori, G. A., and Ghotbi, S. Phase behaviour prediction of petroleum fluids with minimum characterization data, Journal of Petroleum Science & Engineering, Vol 22 (1999) 67-93, 1999
- [12]. Jorda, R. M. Paraffin Deposition and Prevention in Oil Well's, JPT 1605, Trans., AIME, 237, 1966.
- [13]. Karan, K., Ratulowski, J. and German, P. Measurement of Waxy Crude Properties Using Novel Laboratory Techniques, SPE 62945. Presented at the 2000 SPE Annual Technical conference and Exhibition held in Dallas, Texas, 1-4 October, 2000.
- [14]. Kondapi, P., Moe, R. Today's Top 30 flow assurance Technologies: Where do they stand?, OTC 24250. Presented at offshore Technology conference held in Houston, Texas, USA 6-9 May 2013.
- [15]. Lasich, J., Kaila, N. Helitherm-solar power throughput enhancement and heat tracing for heavy oil pipelines, SPE 69726. Presented at 2001 SPE International Thermal Operations and Heavy Oil Symposium held in Poriamar, Margarita Islands, Venezuela, 12-14 March' 2001.
- [16]. Lira-Galeana, C., Firoozabadi, A. and Prauznits, J. M. Thermodynamics of wax precipitation in petroleum mixtures, AIChEJ.42, 239-48, 1996
- [17]. McClafflin, G. G., Whitfill, D. L., Control of paraffin deposition in production, SPE 12204. Presented at the SPE Annual Technical Conference and Exhibition held in San Francisco Oct 5-8, 1983.
- [18]. Pedersen, K. S., Skovborg, P. and Romingsen, H. P. Wax precipitation from north sea crude oils, 4, Thermodynamic modeling, Energy Fuel, Vol 5, 924-32, 1991.
- [19]. Pedersen, K.S. and Michelsen, M., 1997. Letters to Editor, AIChE Journal, 43, (5).
- [20]. Reistle, C. E. Jr. and Laramie, R. Handling Congealing Oils and Paraffin, Fort Worth Meeting, October, 1927.
- [21]. Ronningsen, H. P., Bjoerndal, B., Hansen, A. B., and Pedersen W. B. Wax precipitation from North Sea crude oils: 1. Crystallization and dissolution temperatures, and Newtonian and non-Newtonian flow properties. Energy & Fuels Vol 5 (6), 895-908, 1991.
- [22]. Ronningsen, H.P., Somme, B.F. and Pedersen, K.S. An Improved Thermodynamic Model for Wax Precipitation: Experimental Foundation and Application, paper presented at 8th International Conference on Multiphase 97, Cannes, France, 1997.
- [23]. Rose, S.C and Marsden, S.S. Jr., The Flow of North Slope Crude Oil and Its Emulsion at Low Temperature, American Institute of mining, Metallurgical & Petroleum Eng. USA. Presented at 45th Annual Fall Meeting of the Society of Petroleum Engineers of AIME held in Houston Texas, Oct 4-7, 1970.
- [24]. Shock, D.A., Sudbury, J.D., and Crockett, J.J. Studies of the Mechanism of Paraffin Deposition and Its Control, JPT Vol 23. Presented at Petroleum Branch Fall Meeting in San Antonio, Oct 17-20, 1954.
- [25]. Santosa, J.S.T., Fernandes, A. C., and Giulietti M. Study of the Paraffin Deposit Formation Using the Old Finger Methodology for Brazilian crude oils, Journal of Petroleum Science and Engineering Vol 45 (2004) 47-60, 2004.
- [26]. Sifferman, T. R. Flow Properties of Difficult-To-Handle Waxy Crude Oils. SPE 7409. Presented at the SPE – AIME 53rd Annual Fall Technical conference and Exhibition held in Houston, Oct 1-3, 1978.

- [27]. Sulaiman, A. D. I., Ajiienka, A. J. and Sunday, I. S. Application of piezoelectric energy generated from quartz plus semiprecious metals on wax deposition control, *Journal of Petroleum and Gas Engineering*, Vol 2 (5), PP 93-98, 2011.
- [28]. Tao, R., Xu, X. Reducing the Viscosity of Crude Oil by Pulsed Electric or Magnetic Field, *Energy & Fuels*, Vol 20, 2046-2051, 2006.
- [29]. Tung, N.P., Vuong, N.V., Long, B.Q.K., Vinh, N.Q., Hung, P.V., Hue, V.T. and Hoe, L.D. Studying the Mechanism of Magnetic Field Influence on Paraffin Crude Oil Viscosity and Wax Deposition Reductions, SPE 68749. Presented at SPE Asia Pacific Oil and Gas conference and Exhibition held in Jakarta, Indonesia, 17-19 April 2001.
- [30]. Van Engelen, G.P., Kaul, C.L., Vos, B. and Aranha, H.P. Study on flow improvers for transportation of Bombay high crude oil through submarine pipeline, OTC 3518. Presented at the 11th Annual OTC in Houston, Texas April 30 May'03, 1979.
- [31]. Weingarten, I.S. and Euchner, J.A. Methods for Predicting Wax Precipitation and deposition, SPEPE 121, *Trans. AIME*, 285. Presented at 1986 SPE Annual Technical Conference and Exhibition held in New Orleans, Oct 5-8, 1988.
- [32]. Won, K.W. Thermodynamics for Solid Solution-Liquid-Vapor Equilibria: Wax Phase Formation from Heavy Hydrocarbon Mixtures, *Fluid Phase Equilibria*, 30, 265-279. 1986.
- [33]. Woo, G.T., Garbis, S.J. and Gray, T.C. Long-Term Control of Paraffin Deposition, SPE. Presented at the 59th Annual Technical Conference and Exhibition held in Housto, Texas, September 16-19. 1984.
- [34]. Zougari, M. & Sopkow, T. Introduction to Crude Oil Wax Crystallization Kinetics: Process Modeling, *Ind. Eng. Chem. Res.* Vol 46, 1360-1368, 2007.