Flow Assurance and Comparison of Modelling & SCADA Results for Onshore Crude Oil Trunk Line - A Case Study

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Abstract: **In the quest of energy resources, oil exploration and production is in its peak activity during the present era. Oil and gas fields worldwide are reaching maturity, pushing operations to more challenging areas. During transportation of oil through a pipeline, when the oil temperature is higher than the pipe wall temperature, there will be a dissolved wax concentration gradient between the bulk oil and pipe wall. Crystallization and deposition of waxes occurs if the wall/interface temperature falls below the wax appearance temperature (WAT) of oil being transported. It can affect single wells along with transportation pipelines that are critical to the safe supply of oil to processing facilities. Wax deposition is a very complex phenomenon. Proper pipelines and production equipment is one of the main challenges in Flow Assurance. As remedial costs increase with decreasing production, wax precipitation and deposition significantly influence economy for a field.There are several wax deposition models with different approaches on modeling wax deposition. The basic wax deposition models are Rygg, Rydahland Ronningsen (RRR) model, Matzain model, Hydro model and University of Michigan model. The important element is to illustrate how wax deposition models predict wax build up. The present study intends to analyse the effect of wax deposition on pipelines by RRR model and estimate the temperature profile during summer and winters in entire length of pipeline using MATLAB software &compares it with real time SCADA results. It also estimates and compares the pressure drop and volume of wax deposited along the length of the pipeline.**

Keywords: Flow assurance, modelling, wax

I. INTRODUCTION

The term flow assurance refers to ensuring optimal economical flow of hydrocarbons in production equipment conveying produced fluids, all the way from the reservoir well bore to the treatment facility.[23] In flow assurance, the deposition of high molecular weight paraffin’s, commonly referred to as wax, are causing problems ensuring an economically feasible flow of hydrocarbons. The problems caused by paraffin’s are a result of precipitation of wax near the cold pipeline wall during transportation.[18][32]

The solubility of wax in oil is temperature dependent, decreases with decreasing temperature. At typical reservoir conditions, the wax molecules are dissolved in the oil. As waxy crude or condensates are flowing through the pipelines from the reservoir to the production facilities, the fluid loses heat to the colder surroundings. Consequently, the fluid temperature decreases and a radial temperature gradient over the cross section area of the pipe is established, reaching a minimum value at the pipeline wall. Because the concentration is temperature dependent, a concentration gradient is established by the temperature gradient. If the temperature of a wax-oil mixture drops below the solubility limit of wax, also known as the cloud point or Wax Appearance Temperature (WAT), solid particles start to appear in the solution. If the temperature of the bulk reaches the minimum ambient temperature, that is the wall temperature, there will no longer be a radial temperature gradient across the pipe section, and the precipitation of wax ceases from this point on. Similarly, if all the wax molecules initially dissolved in the solution has precipitated out, further solidification is not possible.

Wax deposition, or the settling of solid wax particles on pipelines and equipment, represents an extensive problem in oil production and transportation. Deposition of wax on pipeline walls, are causing flow restrictions or might, in worst case, plug the pipe entirely. The result is a needfor intervention and possible shut-down of production. Both are expensive and time consuming affaires, but a necessity if reduction in flow rate and production are encountered. To prevent paraffin crystallization or remove existing wax deposits, various tools of chemical and mechanical nature are being used. Chemical methods include paraffin inhibitors/dispersants applied to inhibit the formation of deposits or to modify the WAT preventing agglomeration and deposition, and hot solvents to remediate the deposits already being formed. Examples of mechanical methods are pipeline electrical heating and mechanical scrapping (pigging) which is one of the most used remediation techniques in the field [6] [18] [14][30]

Significant costs are added to the operating cost attempting to prevent and remediate wax deposits. In 2004 the cost of remediation due to pipeline blockage from paraffin deposits were estimated to be in the order of $200,000 when the water depth was at 100 M and in the order of $1,000,000 at water depths near 400 M. [26] Three years later, in 2007, waxy crude oil was estimated to represent about 20% of world petroleum reserves producedand pipelined. With oil production moving further offshore to colder regions and greater depths, the industry is facing increasing challenges, with longer transport distances and more severe wax deposition to be expected. Though, in heavy crude oils with high WATs the presence of wax deposits is also an issue in warmer regions [11].

The most effective way to manage wax deposition, would be to prevent its occurrence in the first place, extensive research is going on, trying to predict precipitation, deposition and growth of paraffin layers [5][30].With sufficientknowledge of relevant conditions, the problem can be dealt with at an early stage of a fielddevelopment project, and thermal insulation to prevent deposition can be planned for. Bydoing so, use of expensive chemical injection and loss of system capacity can be reduced or avoided [20]. However, the understanding and modeling of wax deposition is a complex problem. It involves several disciplines, such as thermodynamics, heat transfer, mass transfer, crystal growth and fluid dynamics. [5][19].

Untreated wax deposition leads to a reduced flow area, and in worst case the deposit may even block the pipe. In order to handle the deposition problem, it is important to know where wax will form, how much wax that will form, how fast the wax will form and how wax deposition can be prevented. To accomplish this, wax deposition models are used. These models predict the wax deposition profile along the pipeline defines potential wax problems and estimates the pigging frequency before production starts up. However, for an operating pipe, the pigging frequency can be determined by Pressure Pulse profiling of deposits combined with tracer injection, and this way the location and extent of the deposit is measured. Usually these data will be correlated up to field data.

In a field pipeline, underestimation by a wax deposition model increases the potential risk of a stuck pig during a pigging operation. On the other hand, overestimation results in too high pigging frequency, and thus unnecessary operational costs.[34] Accurate wax predictions may lead to suitable pigging programs for pipelines, and less wax inhibitors can be used. From an economic point of view correct predictions may reduce the pigging frequency, and thereby reduce the expenses. From an environmental point less use of chemicals is favourable.

II. OPERATIONAL CHALLENGES CAUSED BY WAX DEPOSITION

If deposited wax in a pipeline is left untreated this may lead to major consequences on the operational efficiency of the pipeline system. Over a period of time wax deposit on the pipe wall leads to an increase in the surface roughness and loss of effective diameter, which will increase the pressure drop. The result is reduction in the throughput for the system, and thereby lost production. Wax deposit on the wall of a pipeline leads to increases in pumping pressure due to increase in the wall roughness.[10] A reduced throughput leads to an increased power demand, and problems in the process equipment are also a negative factor. In worst case, wax builds up inside the pipe results in a totally blocked pipe. Production is then stopped and the plugged portion of the pipe must be removed.

Approximately $ 5 Million is the estimated cost of removing a blockage from a pipeline with the help of divers. Production losses during a 40 days downtime, due to a removal operation, are estimates by Elf Aquitaine to cost $25 Million [29] at an oil price of 128.50 $ per barrel [27], and therefore the estimated costs may become even higher. Another terrifying example is a platform that had to be abandoned at a cost of $ 100 Million, due to recurring wax deposition problems in the pipelines.[19]

III. THE WAX DEPOSIT

The wax layer found on the pipe wall will never consist of only wax. A certain fraction will consist of other substances, mainly trapped oil. The oil is trapped in a 3-D network structure of wax crystals. [14] Most wax deposition models predict the rate of deposition of wax crystals and is thereafter multiplies by some factor to account for the trapped oil. In order to predict the wax deposition accurately, it is necessary to know the concentration of oil in the wax deposit. The concentration of oil in a wax deposit is also called the wax porosity. An image of a wax deposit is obtained by polarized light microscopy. The paraffin crystals are observed as white and the trapped oil is black.[13]

Based on field and pilot loop data, an indication is given that the porosity of the deposit varies from one pipeline to another, due to the type of oil, flow regime, degree of turbulence etc.[3] Typically experimental wax porosity values for wax deposition are 0.5-0.9 for turbulent to laminar flow.[24] High shear rates resulted in a hard and brittle deposit, whereas the deposits formed at low shear rates were softer and more elastic. This difference was explained by the difference in oil content of the deposits, and based on this it was concluded that wax porosity decreases with increasing shear rate.[31]

Rygg et al. (1998) used 85 % wax porosity for an oil with less than 0.5 % water, and 60 % wax porosity was assumed for an oil-gas turbulent field.[12] As a base case scenario, Statoil Hydro uses a 60 % wax porosity.[18] The wax porosity affects the wax deposition rate, and high porosity typically results in a thicker and softer wax deposit.[3] However, the wax content of the deposit increases with time, which results in a harder deposit.[16] The nature of the deposit layer also depends strongly on the cooling rate.[14] Higher cooling rate gives a softer and thicker deposit. The deposit becomes looser due to a rapid cooling.

The wall roughness inside a pipe, due to the formation of a wax layer in turbulent flow, influences on the pressure loss in the pipe. However, the wax roughness does not impact on the amount of wax deposited in a pipeline. The literature proves that due to the lack of sufficient data, the wax roughness cannot be estimated accurately and it therefore believed to be an uncertainty factor.

IV. WAX CONTROL MEASURES

There are several methods of controlling wax deposition, but most of them have limitations for longer pipelines. In general four different methods are used when handling the

wax problem. These methods are pigging, pipeline insulation, chemical injection and active heating.[3]
For short lines, approximately 30 km long, insulation limits the temperature loss, which eliminates the need of continuous wax inhibition or regular pigging.[18] Pipeline insulation can include external insulation coating on single pipes or pipe-in-pipe systems.[7]

For long distance transport pipelines regular pigging and chemical injection should be included. [18] The deposit control strategy often consists frequently pigging which leads to a smoothing of the rough wax layer and removes wax back into the oil. [10] The selection of pig type depends on wax properties and operating parameters, though it is said to be more an art than science.[1] There is a danger of getting the pig stuck inside the pipeline during pigging. This may be caused by the deposit being too hard or the wax layer is too thick. [33]

Wax simulations are used to determine the pigging frequency. The software provides estimates of where wax deposition takes place and approximately how much wax that will deposit. In addition, the thickness of the wax layer at the pipe wall is predicted. By comparing the simulation result with an operational criterion, the pigging frequency is determined.[18] In the design phase, a maximum wax layer thickness of 2-3 mm is often used as criterion for when a pipeline should be pigged.[5] This means that as a simulation runs, the wax layer thickness builds up in the pipeline with time, and when the wax thickness reaches 2-3 mm, this gives the time for how frequent pigging should be performed. When the thickness reaches 2-3 mm, then the pipe diameter is reduced by 4-6 mm.

The chemical methods may consist of inhibitors, dispersants and dissolvers.[7] In order to successfully remove a plug, it is vital that the inhibitor has the right concentration at the right place. Certain chemicals may be used for plug melting, because they generate heat when mixed. Combining chemicals with depressurizing or use of coil tubing may increase the probability for the inhibitor to reach the plug.[18]

Heating results in increased temperatures, which moves the system out of the wax stable region. This way plugs may be melted.[18] Such operations can easily be performed if bundles or electrical heated flow lines are installed.[7] Hot flushing consists of hot fluid being pumped into the pipeline. In order to achieve an efficient melting of wax, temperatures must be 20 °C higher then WAT. A high inlet temperature is required, because the flushing fluid is also subjected to cooling.[18]
In addition, the use of pressure pulse and radioactive material should be mentioned. Pressure Pulse technology uses the pressure profile in a pipeline to detect and monitor solid deposits. The pressure profile is achieved from pressure measurements at a location, immediately up-stream of a quick acting valve. The up-stream pressure is measured when the valve is activated. This results in a pressure-time log, which is converted into a pressure-distance log. The location and extent of deposits in a pipeline are given by the pressure-distance log.[4]
Pressure Pulse can be used in combination with tracer injection. One TRACERCO Diagnostics™ technique offered by Tracerco, uses unsealed radioisotope tracing technique. Unsealed radioisotopes are radioactive solid, liquid or gas which follow the fluid in the pipeline. Then, sensitive radiation detectors, which are placed on the outside surface of the pipeline, detect the tracer when it flows in the pipe. Based on this, the wax volume in the pipeline can be estimated. [5]

V. WAX APPEARANCE TEMPERATURE

Wax precipitation is, as presented initially, a phenomena occurring when the temperature of an oil-wax solution drops below the Wax Appearance Temperature (WAT), also known as the cloud point. A solid phase of wax particles, that was earlier in a purely liquid form, appears in the system creating a binary mixture of wax and oil. The WAT is defined at the point where 0.02 mole percent of the liquid has precipitated out of the solution as a solid state [30]. Since the solubility of the solute is temperature dependent, decreasing with decreasing temperature, a lower cloud point results in later occurrence of wax precipitation. Experiments have demonstrated that the WAT is mainly depended upon temperature and the total wax content of the solution [35].
The WAT determines the onset of wax precipitation, and thus separates a waxy and a waxy-free zone. Below the WAT there is a region with waxy crystals in a solid phase and oil as the liquid phase. Above the WAT a single liquid phase region exists in which the wax has not precipitated out of the solution yet, and remains dissolved in the oil [35].The position of the wax appearance boundary is, as a result, inferred from the temperature profile [35].
Modeling of wax precipitation and deposition is highly sensitive to the WAT prediction ability [25].There are several methods to determine the WAT, among those are Cross Polar Microscopy (CPM) and Differential Scanning Calorimetry (DSC). Because of the importance of the WAT in the modeling, it is recommended to make use of two independent techniques when determining the WAT to obtain a sufficient degree of accuracy [33][34].

VI. WAX MODELING

In 2011, Aiyejinaet. al. did an extensive examination of the state of research regarding wax formation in oil pipelines. Among others, they identified that many existing wax deposition models assumes independence of temperature and concentration gradients [5][34] noted that such independency is valid for laminar flow only. For turbulent flow regimes, as encountered in oil owing pipelines, the concentration field is correlated to the temperature field, and must, in order to obtain correct modeling, be considered [34].
Burger, et al., conducted in 1981 a comprehensive study of wax deposition mechanisms, and their work, is still one of the most cited references in the field. They identified

molecular diffusion, Brownian diffusion, shear dispersion and gravitational settling as the possible mechanisms responsible for wax deposition [8]. A review of the modeling of wax deposition mechanisms was done by Azevedo and Teixeira in 2003. They acknowledgedmolecular diffusion of paraffin's, as described by Burger et al., to be the dominant deposition mechanism, and argued that experimental evidence suggests that gravity settling and shear dispersion do not contribute significantly in the process [5][1]. However, they found that there was not enough experimental evidence to exclude the possibility of Brownian diffusion of solid wax crystals taking part [5].

In a paper from 2011, Singh et al. states that the overall consensus in the field, is that the dominant wax deposition mechanism is molecular diffusion in viscous sub-layer driven by the radial diffusion of n-paraffin's, following Fick's law [10]. Most wax deposition models available in literature make use of molecular diffusion as the sole mechanism for wax deposition prediction [5].

The model presented in this report, is based upon heat and mass transfer analysis. The method is developed by a research group at the University of Michigan [18][14]. Molecular diffusion is considered the dominant mechanism for wax deposition. The heat and mass transfer phenomena are accomplished combined and the precipitation kinetics in theviscous sub-layer is included to describe the wax deposition behaviour in turbulent flow. The Michigan Wax Predictor (MWP), as the method is called, has shown to be applicable for a range of flow conditions and is recognized as a correct analogy for correlated heat and mass transfer and therefore chosen in this project [18][14][1][33]

VII. RYGG, RYDAHL AND RONNINGSEN (RRR) MODEL FOR WAX DEPOSITION

The RRR (Rygg, Rydahl and Rønningsen) model is a multi-phase flow wax deposition model which predicts wax deposition in wells and pipelines. The multi-component wax model continuously estimates the wax precipitation along the pipeline and the viscosity of the composition. The wax deposition is then estimated from the diffusion of wax from the bulk towards the surface of the pipeline, due to temperature gradients and shear dispersion effect. The inner pipe wall friction is varied due to wax deposition.[1]

Deposition in the RRR model is based on molecular mechanisms which enhance the wax deposition. The volume rate of wax deposition by molecular diffusion [1] for a wax forming composition i is found from

$$Vol^{diff}_{wax}=\sum^{NWAX}_{i=1}[D_i(c_i^b-c_i^w)S_{wet}MW_{i.}2rl\pi/\delta\rho_i] \quad \ldots 1$$

Where c_i^b&c_i^w the molar concentrations of the wax component i dissolved in the oil phase in the bulk and at the wall respectively (mole/m^3), S_{wet} is the fraction of the wetted circumference, NWAX is the number of wax components, MW_I is the molar weight of wax component i (kg/mole), D_i the density of wax component i (kg/m^3), r is the current inner pipe radius (m) and L is the length of the pipe section (m). D is the diffusion coefficient, and the Hayduk-Minhas correlation (m^2/s) is used to calculate the diffusion coefficient. δ is the thickness of the laminar sub-layer (m).

The thickness of the laminar sub layer in the pipeline is given by [2] and α is a allowed correction factor for tuning thickness of the wax layer to experimental data.

$$\delta=\alpha\times 11.6\times\sqrt{2}\times(D/Re)\times(I/\sqrt{f}) \quad \ldots 2$$

Given that D is the pipe diameter (m), Re is the Reynolds number and f is the friction factor.

VIII. TEMPERATURE DRIVEN WAX DEPOSITION IN PIPELINE

As the produced fluid enters the well, the reservoir pressure and temperature gradually decreases. At the wellhead the fluid normally has high pressure and a moderate temperature. Crude oil from the reservoir will typically flow into the production pipeline around 60°C.

Temperature at any distance 'x' meters [4] from pipeline is given

$$T_x=T_{amb}+(T_{inlet}-T_{amb})\times e^{(-U\times\pi\times D\times x/(m\times Cp))} \quad \ldots 3$$

Where T_x is the fluid temperature at any distance x from pipeline, T_{amb} is the ambient temperature outside of the pipeline, T_{inlet} is the fluid inlet temperature,T_{outlet} is the fluid outlet temperature, L is the length of the pipe, d is the pipe diameter, m is the mass rate flowing fluid inside the pipe and Cp is the heat capacity fluid. U is the heat transmission coefficient and a large U value leads to a rapid cooling.

IX. PRESSURE DROP IN A PIPELINE

As we move along length of pipeline, more wax is pressure deposited due to decreasing temperature. Darcy Weisbach equation is used in this study to compute pressure drop along length of pipeline.

$$\Delta P=f\times\rho\times L\times V2/(2\times D) \quad \ldots 4$$

Where f is given as friction factor of pipeline,L is length of pipeline in meter,V is velocity of flow in m/s,ρ is density of oil in kg/m^3,D is diameter of pipe in meter.

The fluid flow in a pipeline is either in laminar flow throughout the pipe, or just in the thin laminar sub-layer close to the pipe wall. During the cooling process of the pipeline, there is a temperature gradient across the laminar sub-layer.[13]

The solubility of wax is strongly dependent on temperature. [1] When the oil temperature is above the WAT, oil is not saturated with dissolved wax, and therefore the concentration gradient of dissolved wax is effectively zero. [10] The first wax crystals start to form at the Wax Appearance Temperature. Keep in mind that wax deposition only occurs when the temperature of the deposition surface in a pipe, not the average oil temperature, is below the oil WAT.[8]

With turbulent flow, lateral motion of the fluid eddies lead to rapid transport of precipitated or dissolved waxy crystals. Along the pipeline there will be an essentially uniform lateral concentration of precipitated and dissolved materials throughout the turbulent core and the buffer layer. The transport across the laminar sub layer is slower. In this area the net rate of transport is controlled. Wax deposition mechanisms contribute to the lateral transport of material.[13] Some wax deposition mechanisms help deposit grow, other mechanisms do the opposite.

As the cooling continues, the gradient increases until it reaches a steady value. Decreasing temperature in the pipeline leads to decreasing radial temperature coefficient and diffusion coefficient. Just below the WAT the wax deposition rate rises to a maximum value. Less wax is dissolved as the temperature decreases, and as the temperature in the pipeline becomes closer to ambient temperature the wax deposit rate gradually falls off. [10] The wax deposition disappears when there is no temperature difference between the oil and the wall, even if the oil temperature is far below WAT.[7]
It should be mentioned that the wax deposition rate depends on oil composition, oil temperature, ambient temperature around the pipe, flow conditions, pipeline size, insulation, and the system pressure.

X. CASE STUDY

ABC field was put on production in early 1990's. Presently the production from ABC field is about 550 m^3/D. At ABC Group Gathering Station (GGS) the entire crude is heated up to 60^{o}C during winter and 50^{o}C during summer and pumped in crude dispatch line. Due to viscous nature of crude, high pressure drop is observed during winters. Chemical treatment with xylol and Pour Point Dispersants (PPD) is being done to keep the crude above its pour point.

Chemical treatment during winters in addition to routine heating before pumping the ABC GGS crude to XYZ GGS is done to maintain its viscosity within desirable limits for back pressure reduction. Intermittent pumping of crude and water is being done to reduce the back pressure. The lines are being pigged every month for scrapping the wax deposition during winters and once in every two months during summer. Presently pumping from ABC GGS to XYZ GGS is carried out with the help of two reciprocating pumps of discharge capacity 12 m^3/hr each with pressure rating of 50 kg/cm^2.

The 8 inch × 25 km pipeline is buried at a depth of 1.2 meter and having nominal diameter 8 inches with Poly urethane insulation which is 2.5 mm thick. The trunk line carries crude oil of 31 API and density of 0.843 g/cc. Physical properties of crude and pipeline dimensions is given in table 1.

Present study helps to analyze the temperature, pressure drop and volume of wax deposited in particular length of pipeline by molecular diffusion. MATLAB software is used for modeling the temperature profile as well as the pressure drop along length of pipeline during summer and winter season.

XI. RESULTS

Temperature profile of pipeline is given in fig. 5 during summer (refer annexure 1 for MATLAB codes). Ambient temperature is reached at 13058 m and WAT at distance of 720 m. Temperature profile of pipeline during winter is given in fig. 6 (refer annexure 2 for MATLAB codes). Ambient temperature is reached at 14118 m and WAT at 580 m. Pour point is reached at 2185 m. Pressure drop in the pipeline is received from fig 7 (refer annexure 3 for MATLAB codes). Pressure drop experienced is 47 kg/cm^2. So along 25 km pipeline the pressure drop is 1.88 kg/cm^2.Volume rate of wax deposited by molecular dispersion by RRR model is also calculated as 6.08×10^{-8} m^3/s and implies total volume of 5.25×10^{-3} m^3/day. Total mass of wax deposited is 4.78 kg/day and 143.4 kg/month.The modeling results prove the amount of wax which is deposited in the pipeline is very high and it's given in fig.8 (refer annexure 4 for MATLAB codes).

CONCLUSION

- Despite the fact that crude is being heated to 60^{o}C during winter and 50^{o}C during summer season, wax deposition is on a higher side & is the main reason for pressure drop. So it is suggested that to maintain this temperature and if possible further increase temperature up to 65^{o}C.
- MATLAB & SCADA results are in very good agreement with each other with minimal error (fig 1-4).
- It is observed that chemical injection during winters has considerably reduced the wax formation thereby reducing back pressures.
- Increasing the pigging frequency during winters helps to avoid wax deposition.

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FIGURES

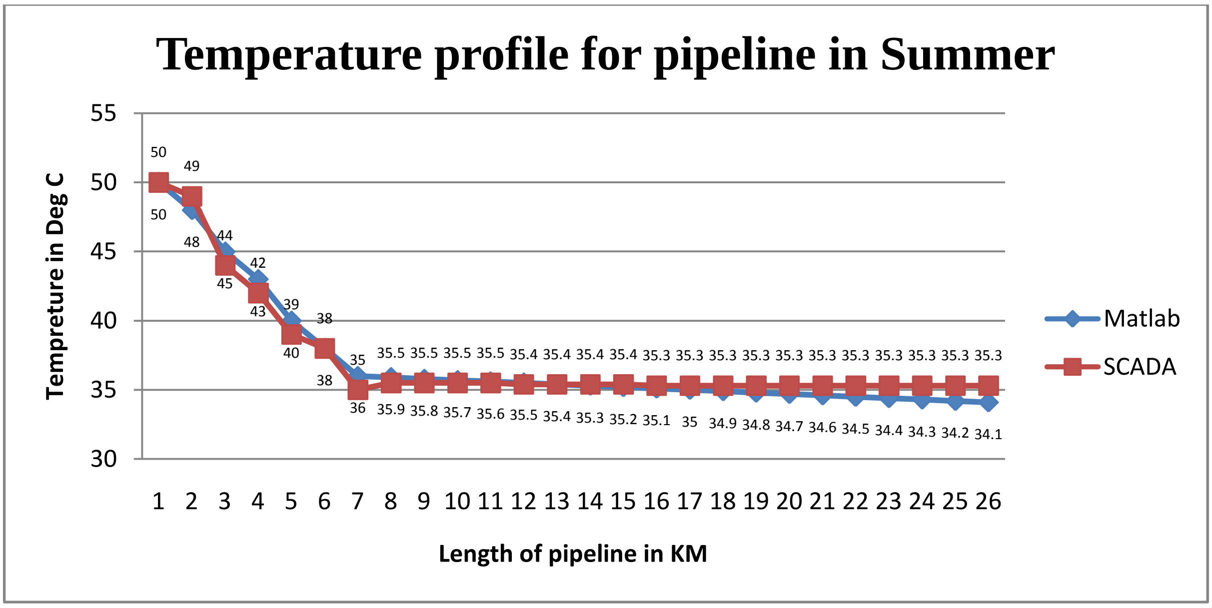

Fig. 1 Comparison of MATLAB & SACDA temperture results during summer

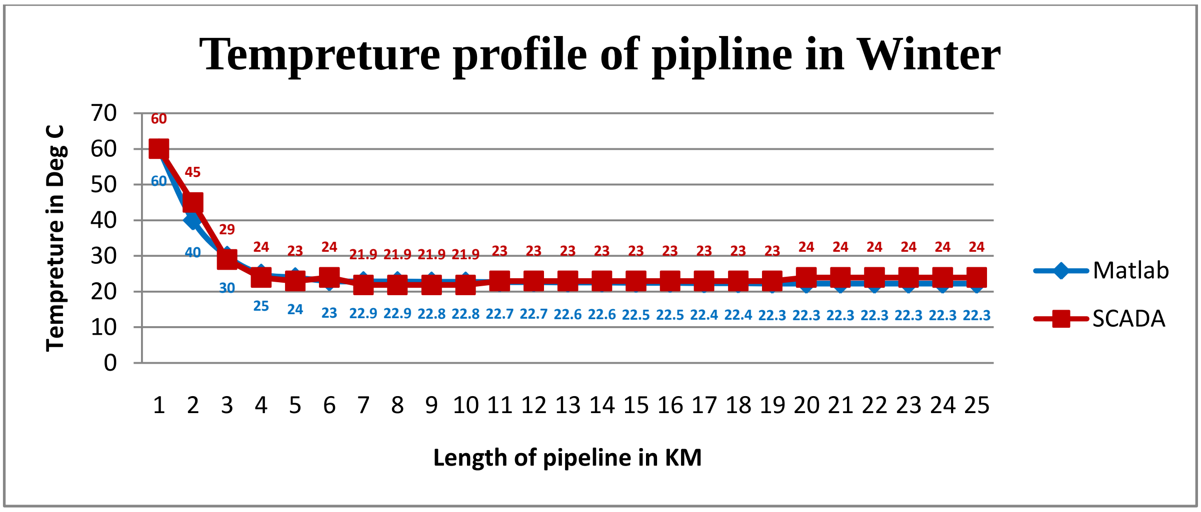

Fig. 2 Comparison of MATLAB & SACDA temperture results during winter

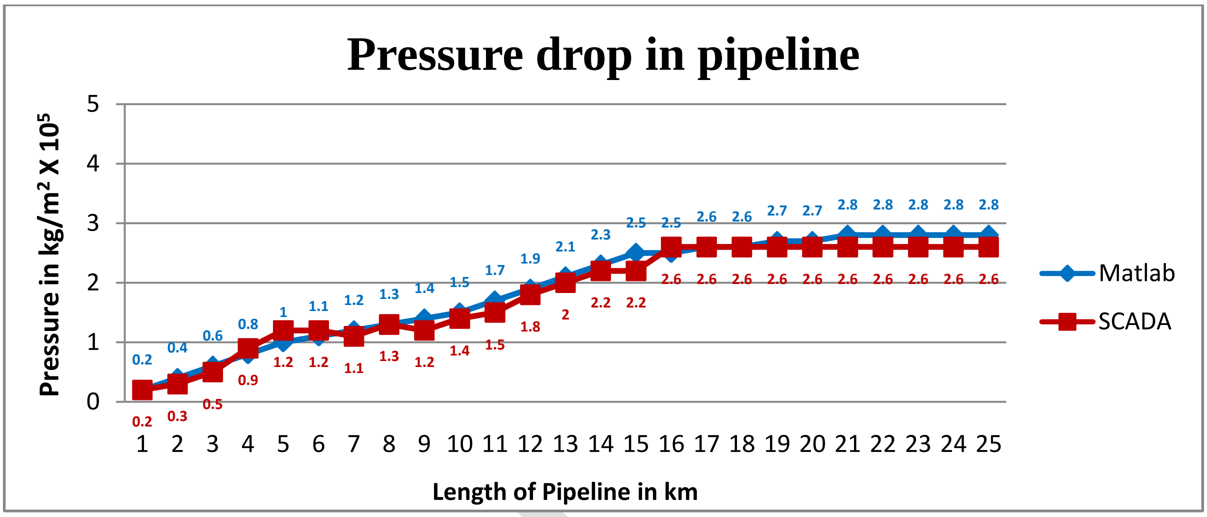

Fig. 3 Comparison of MATLAB & SACDA pressure dropresults during winter

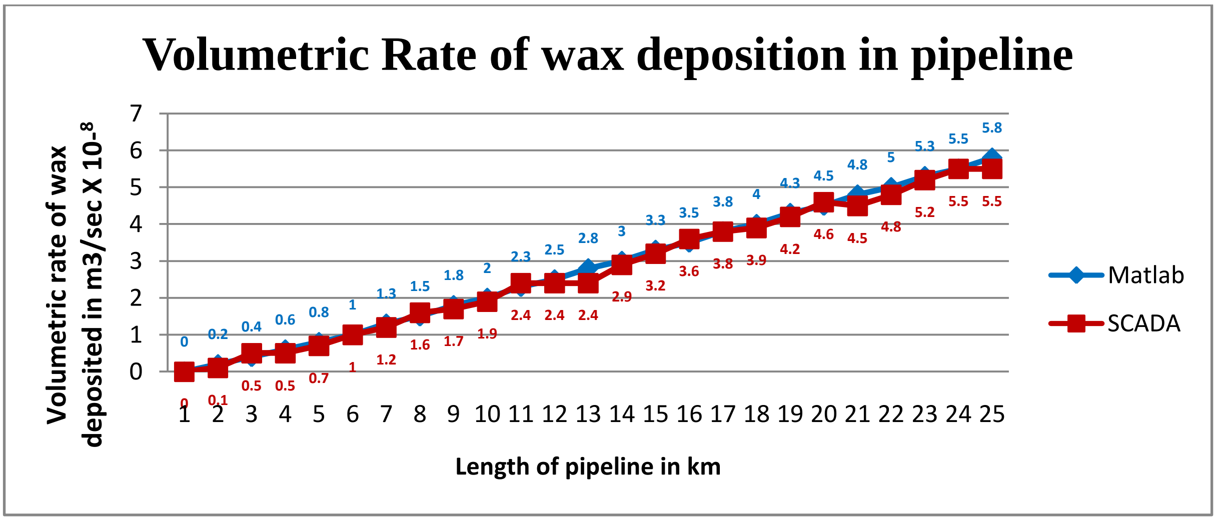

Fig. 4 Comparison of MATLAB & SACDA wax depositionresults during winter

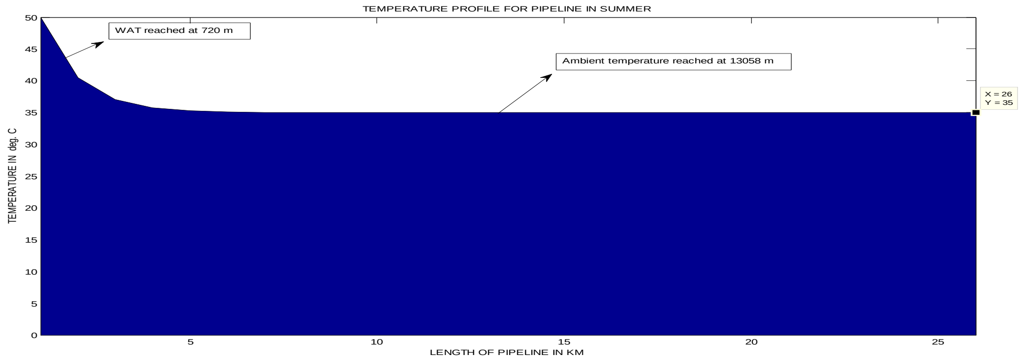

Fig. 5 MATLAB temperature profile during summer

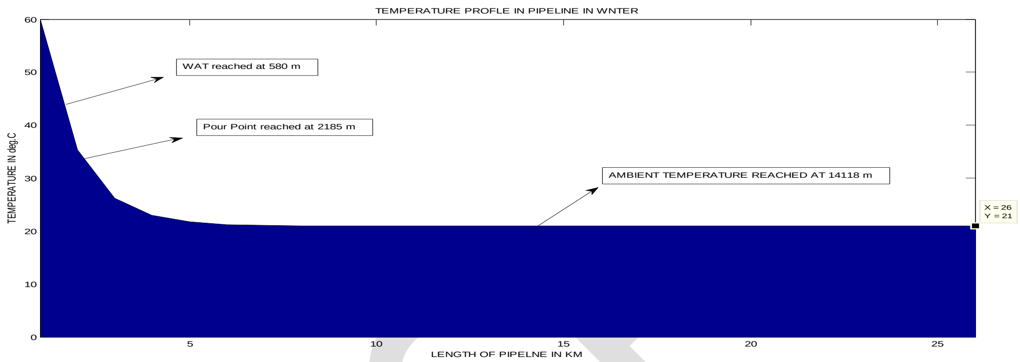

Fig. 6 MATLAB temperature profile during winter

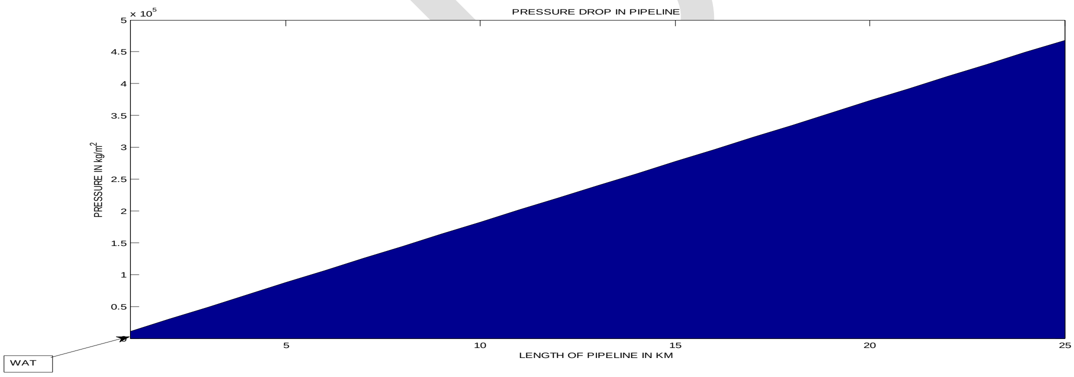

Fig. 7 MATLAB pressure drop profile during winter

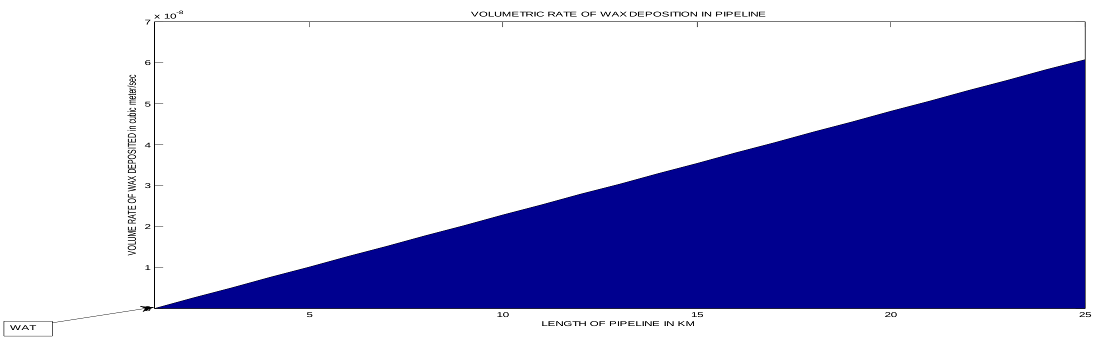

Fig. 8 MATLAB wax deposition profile during winter

Table 1: Physical properties of crude and pipeline dimensions

Internal Diameter(m)	0.205
External Diameter(m)	0.212
Inlet Temperature(^oC)	60(Winter) 55(Summer)
Ambient Temperature(^oC)	21(Winter) 35(Summer)
Density(g/cm^3)	0.843
API gravity(^oC)	34
WAT and Pour Point (^oC)	43(Winter)/33(Summer)
Wax content (%)	12
Specific gravity	0.8531
Water Content(%v/v)	10