

Development and Application of an Asphaltene Deposition Tool (ADEPT) for Well Bores

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ABSTRACT: Asphaltenes often tend to deposit in reservoirs, flow lines, separators, and other systems along production lines causing significant production loss due to restricted oil flow or damages caused to the units and instruments used along the flow lines. Asphaltenes are typically stable in the oil; however, changes in conditions such as temperature or pressure or compositional changes can trigger the phase separation and resultant deposition of these asphaltenes on the surfaces encountered along the flow. Hence, it is required to be able to forecast the possibility of precipitation of asphaltenes for given operating conditions and quantify the amount of deposition. In this work, the development of an asphaltene deposition tool (ADEPT) that can predict the occurrence and calculate the magnitude and profile of asphaltene deposition in a well bore is discussed. The simulator consists of a thermodynamic module and a deposition module. The thermodynamic module uses the Perturbed Chain Statistical Associating Fluid Theory (PC SAFT) equation of state to describe the phase behavior of oil, which is first characterized by using thermodynamic properties such as saturation points and asphaltene onset pressure data and physical properties such as the density of the oil. The deposition module is then used along with input from the thermodynamic module to calculate magnitude of asphaltene deposition along the length of well bore/pipe lines. The mathematical model used in the deposition module is first benchmarked and validated by comparing the simulation results against the experimentally measured asphaltene deposition flux in a capillary scale deposition experiment. The simulator was then used to study deposition in two field cases, for which measurements of asphaltene deposition profile were reported in the literature. This study demonstrates the development and application of a simple yet comprehensive simulator that can be easily integrated with other commercial flow simulators, facilitating quick calculations of the change in the asphaltene deposition profile and magnitude with change in operating conditions as the production continues. It is shown that the simulator enables operators to perform quick sensitivity studies and map out operating envelopes to avoid potential risk zones.

INTRODUCTION

Asphaltenes are the heaviest and the most polarizable fraction of the crude oil. These are defined, on the basis of their solubility, as the class of crude oil components that are soluble in aromatic solvents such as toluene or benzene and insoluble in low molecular weight alkanes such as *n*-heptane. Similar to waxes and gas hydrates, asphaltenes tend to cause arterial blockage of flow lines and other production topside facilities used in the oil industry, such as separators and heat exchangers. Asphaltenes also tend to deposit in reservoirs. However, asphaltenes pose a special challenge compared to these other components because of the facts that asphaltenes are not well characterized and asphaltene deposition can occur even at high temperature.

Asphaltenes are originally stable in oil. However, the phase stability of asphaltenes in oil is sensitive to the pressure and temperature conditions and other asphaltene precipitating conditions, such as oil composition changes, potentially caused by the addition of light gases, solvents, and other oils in commingled operations or even changes due to contamination from other sources. If these asphaltene precipitating conditions are met, asphaltenes start phase separating from the oil and tend to deposit on walls of the well bores or pipelines. The presence of

deposit can severely affect the production rate of oil, and the consequent intervention costs can sometimes be as high as USD 500 000 for an on-shore field to USD 3 000 000 or more for a deepwater well, along with the cost of lost production that can be more than USD 1 000 000 per day.¹

These problems, therefore, necessitate the ability to predict not only the possibility of asphaltene precipitation or phase separation under various operating conditions but also its deposition tendencies. The phase stability of asphaltenes can be well described by thermodynamic models, and this has been the subject of several publications. Solubility models described by equations of state have been extensively used to study the phase behavior of asphaltenes in oil. The works by Burke et al.,² Nghiem et al.,³ Akbarzadeh et al.,⁴ Nikookar et al.,^{5,6} and Pazuki et al.⁷ are some of the several publications that demonstrate the use of cubic equations of state in modeling the stability of asphaltene in oil. The application of SAFT (Statistical Associating Fluid Theory) based equation of state models has also been

Received: May 27, 2011

Revised: September 19, 2011

Published: September 20, 2011

presented in the work of Ting et al.,⁸ Gonzalez et al.,⁹ and Vargas et al.¹⁰ However, the knowledge of possible asphaltene precipitation, although critical, is only a part of the solution. It is equally important to predict the transport of these precipitated particles and identify their deposition tendencies. However, this line of research work has been severely plagued as a result of the difficulties associated with the complexity of these asphaltene structures and an insufficient understanding of the deposition tendencies of these asphaltenes.

Nevertheless, there are a few studies published in the literature focusing on the prediction of asphaltene deposition in pipelines, clearly illustrating the importance of this problem in the oil industry. The work of Ramirez et al.¹¹ describes the usage of a molecular diffusion model to represent asphaltene deposition. Jamialahmadi et al.,¹² in their work, have developed a mechanistic model based on three parameters that they have identified in their system, using experimental results to estimate these parameters. This model was further used by Soulgani et al.¹³ to predict asphaltene deposition for an Iranian oil field. Vargas et al.¹⁴ proposed a deposition simulator based on species conservation equations coupled with thermodynamic modeling of oil with PC SAFT. Eskin et al.¹⁵ have used particle flux mass transfer expressions for turbulent flows to model the deposition process. The required model parameters are obtained by fitting the model predictions to the deposition results obtained from their Couette flow device. They have shown a quantitative comparison between predicted and measured deposition flux for a field case. A review of the existing literature reveals that there is a lack of both qualitative and quantitative comparisons of the prediction of asphaltene deposition profiles with lab-scale and field-scale deposition profiles. The difficulty of this problem coupled with the lack of complete field data substantially impairs the efforts of researchers in this area to be able to compare their new simulator predictions to field observed situations. To be able to do so, a complete set of input data that possibly includes information about the oil properties, such as density, saturation pressure, and asphaltene onset conditions, is required, along with samples of oil that can facilitate laboratory scale deposition experiments. Several other parameters pertinent to the aforementioned simulators may also be required. All these data are very rarely available, and hence, a systematic data acquisition protocol is required, which is a subject of future research.

Considering all these factors, the work described in this study discusses the development of a deposition simulator used for the prediction of asphaltene deposition in oil well bores and pipelines. The study elucidates the usage of a simple, yet comprehensive, mathematical model that depicts the precipitation, aggregation, and deposition of asphaltenes, along with their transport with oil as the oil flows up the well bore or flows along the pipelines and encounters varying conditions such as temperature, pressure, etc. Though this new work is a continuation of the model by Vargas et al.,¹⁴ it employs a modified mathematical model that can be successfully used for conditions that prevail in turbulent flows in well bores. In this study, the structure of the proposed deposition simulator is discussed. The deposition of asphaltenes in a capillary scale pipe is carried out, and the deposition profile measurements for an oil–precipitant combination are reported. The deposition model is successfully used to predict the deposition profile in these capillary scale experiments, demonstrating the applicability of the developed model. The capillary scale experimental data can be used to estimate parameters required in the model by comparing the simulator

predictions against the experimental observations for an oil sample that needs to be investigated for the possibility of well bore asphaltenes deposition. The deposition simulator is then used to predict asphaltene deposition for two field cases with asphaltene deposition problems and for which the deposition profile measurement data was available. The oils are first thermodynamically modeled, and then, the thermodynamic model is integrated with the deposition simulator to predict the deposition of asphaltene along the axial length of the well bore.

It should be noted that the overall emphasis of this study was to develop a comprehensive simulator that is still simple enough to allow easy integration with other commercially available multiphase flow simulators (e.g., OLGA, PIPESIM, FLOWASTA, etc.) and that is also computationally efficient. In spite of the uncertainties of data involved and even lack of data in some cases, this study demonstrates that the proposed simulator performs well in obtaining a qualitative as well as quantitative description of the asphaltene deposition profile.

■ CAPILLARY DEPOSITION EXPERIMENTAL METHOD

The capillary deposition experiment has already been explained in great detail elsewhere,¹⁶ and hence, only a short description of the set up is provided here. A schematic diagram of the deposition test apparatus is shown in Figure 1. The deposition of asphaltene occurs in a long capillary tube (~30 m), 0.02–0.04 in. inner diameter (i.d.). Two high-pressure syringe pumps were used to inject fluids at constant flow rates. A pressure transducer was used to measure the pressure drop across the capillary tubing continuously, and the pressure was recorded by a computer. The capillary tube was immersed in a water bath to maintain isothermal conditions. For a typical experimental run, to study the asphaltene deposition in the capillary, the oil stream from pump 2 (Figure 1) is mixed with the precipitant (*n*-alkane) from pump 1 by flowing through a mixing node within an ultrasonic bath to ensure complete mixing. The total flow rate was maintained within a laminar flow regime. Toluene was pumped through the capillary to measure its actual radius prior to each test. At the end of each experimental run, the in situ deposition profile along the capillary tube was measured using a novel nondestructive technique.^{17,18} A constant-pressure nitrogen source was connected to the capillary inlet. The remaining liquid inside the capillary was gradually displaced out from the outlet and weighed by an electronic balance. The recorded weight of effluent as a function of time was then used to calculate in situ deposition thickness. Alternatively, an oil immiscible, viscous fluid such as glycerin could be injected from one end of the capillary under constant flow rate after the remaining oil/precipitant mixtures had been flushed out by nitrogen. Pressure buildup at the injection port was continuously recorded with a pressure transducer connected to a computer, while the capillary outlet was open to the atmosphere. Under constant flow rate, the variation of pressure drop was determined by the local effective diameter of the capillary, which was used to retrieve in situ deposition thickness.

Asphaltene content in the oil is generally very low, and asphaltene deposition rates are also considerably low; hence, to get significant amounts of deposits, a large volume of sample is required. Especially in the case of appropriately scaled laboratory scale experiments that mimic the turbulent conditions that are typical in the field. The usage of a capillary deposition setup therefore becomes attractive. However, it should also be noted that there exists a laminar sublayer near the wall of the well bores/pipelines that dictates the deposition process and, in this work, it is proposed that the laminar conditions in the capillary deposition experiment mimic this laminar sublayer adjacent to the turbulent core.

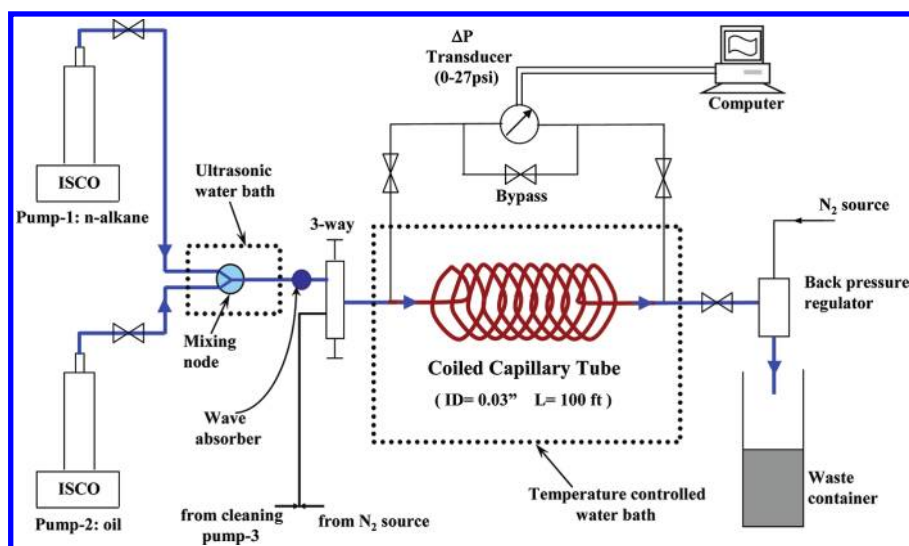


Figure 1. Schematic representation of the capillary deposition experimental setup used to measure the deposition profile of asphaltene in a stainless steel capillary pipe.¹⁶

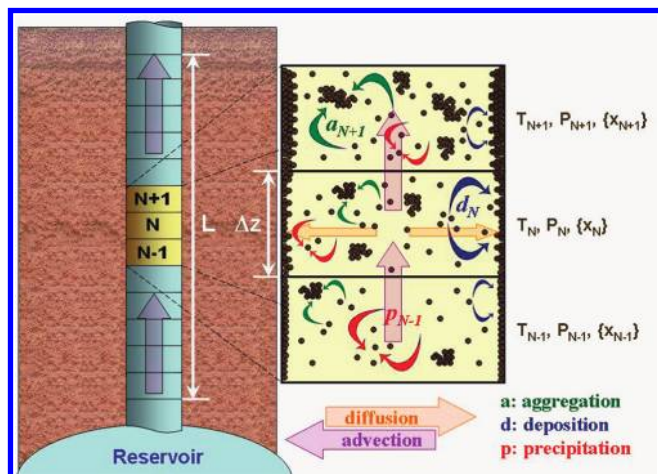


Figure 2. Figurative depiction of the asphaltene phase transition stages and consequent kinetic processes occurring as the oil flows up the well bore.

MATHEMATICAL MODEL AND SIMULATOR STRUCTURE

At reservoir conditions, the asphaltenes may be stable and soluble in oil. However, as the oil flows up the well bore (Figure 2), the pressure and temperature of the oil decrease. A change in these conditions can make the asphaltenes that are originally dissolved in the oil unstable, causing the phase separation of asphaltenes. This process of formation of primary particles is termed as the precipitation of asphaltenes. These precipitated particles are then carried along with the flow of the oil phase. As discussed in the work of Vargas et al.,¹⁴ it is proposed that these primary particles are susceptible to deposit on the walls of the well bore through the deposition step. These primary particles can also further aggregate with each other to form larger sized aggregates through the aggregation step. Thus, the mathematical model (nondimensional) can be written as the material balance of these primary particles in the transient state over a control volume (Figure 2) of the pipe/well bore and is

represented by the following equation:

$$\frac{\partial C}{\partial \theta} = \frac{1}{Pe} \frac{\partial^2 C}{\partial Z^2} - \frac{\partial C}{\partial Z} + r_p - Da_{ag}C - Da_dC \quad (1a)$$

$$r_p = Da_p(C_f - C_{eq}) \text{ when } C_f > C_{eq} \quad (1b)$$

$$r_p = r_{diss} = -k_{diss}Da_pC \text{ when } C_f < C_{eq} \quad (1c)$$

$$\frac{\partial C_f}{\partial \theta} = -\frac{\partial C_f}{\partial Z} - r_p \quad (1d)$$

The required initial and boundary conditions are

$$C(\theta=0, Z) = 0 \quad (2a)$$

$$C(\theta, Z=0) = 0 \quad (2b)$$

$$\left. \frac{\partial C}{\partial Z} \right|_{(z=1)} = 0 \quad (2c)$$

where the dimensionless parameters are

$$Pe = \frac{V_z L}{D}, Da_{ag} = \frac{k_{ag} L}{V_z}, Da_p = \frac{k_p L}{V_z}, Da_d = \frac{k_d L}{V_z} \quad (2d)$$

$$C = \frac{C'}{C_0}, C_f = \frac{C'_f}{C_0}, C_{eq} = \frac{C'_{eq}}{C_0}, Z = \frac{z}{L}, \theta = \frac{t V_z}{L}$$

The last three terms in eq 1a are the kinetics of precipitation, aggregation, and deposition, respectively. In this work, for simplicity sake, these are modeled as first order kinetic processes characterized by the corresponding rate constants. Similar to the work of Vargas et al.,¹⁴ the precipitation rate is modeled as dependent on the degree of supersaturation of the oil. C_f is the concentration of asphaltene present in the oil phase, and C_{eq} is the concentration of asphaltene that can be present in the oil phase as a stable phase without phase separating (saturation concentration) at that pressure and temperature condition. If the

concentration of asphaltenes is above this value, then asphaltene starts precipitating out of the oil phase with the rate k_p , and the difference between these concentration values drives the amount of asphaltenes precipitated. The value of C_{eq} is calculated using the thermodynamic model of the oil. When the asphaltene concentration falls below C_{eq} , in situations such as described in the later part of this paper (in well bores or pipelines beyond the bubble point, asphaltene precipitating lighter components escape the oil making the oil a better solvent for asphaltenes), asphaltenes start dissolving back into the oil phase. k_{diss} is a factor used to express dissolution kinetics, as compared to precipitation kinetics.

The mathematical model used in this study is similar in structure to that described in the work of Vargas et al.¹⁴ However, the model developed by Vargas et al.¹⁴ for capillary-scale deposition was a two-dimensional model, and the transport of these primary particles in both the radial and the axial coordinates was taken into consideration. Only the diffusion of particles in the radial direction was considered, while the diffusion in the axial directions was neglected. However, it is well-known that, for turbulent flows in well bores, the eddy diffusion due to the fluctuating velocity components dominates molecular diffusion; the effective diffusivity is enhanced and almost eliminates radial gradients and causes significant mixing in the axial direction. Hence, in this work, we propose to use an axial dispersion model¹⁹ that has been successfully used to model species transport in turbulent pipes.¹⁹ In this case, the diffusion term used in the model of Vargas et al.¹⁴ gets replaced by the axial dispersion coefficient D . At a high Reynolds number (Re), D depends only on fluctuating velocities in the axial direction that cause mixing. The value of D can be determined experimentally, using transient experiments with nonreactive tracers. A correlation for D exists in the literature, which enables the successful application of this model for turbulent flows. However, this model can also be used for laminar flow, such as the capillary deposition experiments studied in this work, if the pipe is long enough and the following condition is met:¹⁹

$$D_m \bar{t} / R^2 > 0.125 \quad (3)$$

where, D_m is the particle diffusivity, \bar{t} is the residence time, and R is the radius of the tube. For the range of operating parameters considered in the capillary deposition experiments, this condition (eq 3) was satisfied, and hence, it was reasonable to use the axial dispersion model to study transport of asphaltene particles in the capillary pipe as well. For laminar flows, such as in the case of capillary deposition experiments, the dispersion coefficient is calculated using the following equation:¹⁹

$$D = D_m + \frac{V_z^2 R^2}{48 D_m} \quad (4)$$

For turbulent flows, such as in well bores, the dispersion coefficient was computed from the relation between Reynolds number and radial Peclet number reported by Naumann.²⁰ The radial Peclet number, defined as $Pe_r = 2RV_z/D$, typically is around 5 for $Re \sim 100\,000$.

It should also be noted that this model is one-dimensional and is therefore computationally less expensive compared to the two-dimensional model developed previously.¹³ The well bores are generally very long pipes that have L/D_p (D_p is the diameter of the pipe) typically ranging in the order of 40 000, and hence, the discretization points required in the axial direction are very high.

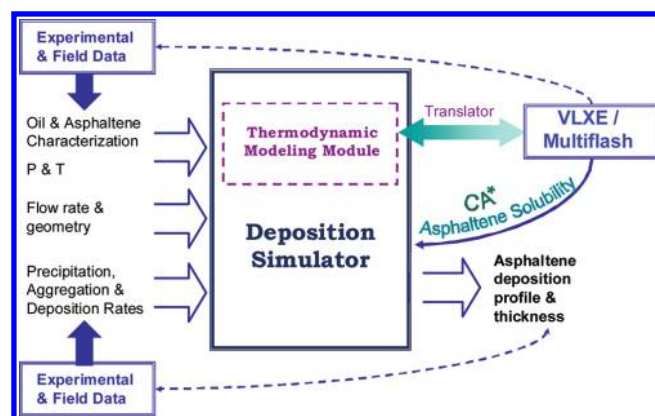


Figure 3. Schematic representation of the asphaltene deposition simulator with elucidation of the structure and the internal modules.

Consequently, using a one-dimensional model in the axial direction drastically decreases the number of equations that need to be solved versus a 2D model that requires discretization in both radial and axial directions. A simulation of asphaltene deposition in a well bore with the one-dimensional model used in this work requires ~ 1 min to run on an Intel Core2 Duo CPU with 2.44 GHz processor speed, while the previous two-dimensional model needed ~ 10 min. Faster simulation models enable engineers to perform faster parameter sensitivity studies in reasonable time. The usage of a one-dimensional model also enables easy integration with commercial flow simulators such as OLGA and the like, which is one of the key objectives of this study.

The transient one-dimensional model is discretized in the axial direction, which results in a set of coupled ordinary differential equations. These differential equations coupled with the mass balance of asphaltene in the oil phase are then solved using the DIVPAG (double precision initial value Problem—Adams Moulton's—Gear's method) subroutine in IMSL (International Mathematics and Statistical Library).

The structure of the proposed deposition (asphaltenes deposition tool—ADEPT) simulator is shown in Figure 3. At the heart of the ADEPT simulator is a thermodynamic module that is required to accurately describe the phase behavior of the oil at the varying temperature and pressure conditions of the well bore. Certain physical and thermodynamic properties such as density, saturation pressure, and asphaltene onset pressure conditions are required as input to this module. With these inputs, parameter estimation for the thermodynamic model can be performed to obtain an accurate model to describe the solubility of asphaltene in the oil along the axial length of the well bore as the pressure and temperature conditions vary. In this study, we have used the PC SAFT (Perturbed Chain Statistical Associating Fluid Theory)²⁰ equation of state to model the oil. PC SAFT, a modified version of SAFT,²¹ has been successfully used by Ting et al.,⁸ Gonzalez et al.,⁹ and Vargas et al.¹⁰ to study the phase behavior of asphaltene in oil. These previous studies have demonstrated that PC SAFT accurately models the variation of asphaltene stability in oil due to changes in pressure and temperature as well as gas injection of N_2 , CO_2 , methane, and ethane²² and other compositional changes.²³

The deposition module consists of the mathematical model for asphaltene deposition in pipe lines, as discussed earlier in this paper. This module requires information regarding the stability

Table 1. Physical Properties and Compositional Information of Crude Oil M1 Used in Capillary Deposition Studies

| oil properties (M1) | |
|----------------------------|------|
| saturates, wt % | 62.9 |
| aromatics, wt % | 21.4 |
| resins, wt % | 13.3 |
| asphaltenes, wt % | 2.42 |
| ρ (precipitant), g/mL | 0.74 |
| ρ (oil), g/mL | 0.85 |
| ρ (mixture), g/mL | 0.82 |
| μ (mixture), mPa s | 3.95 |

Table 2. Experimental Operating Conditions Set for Capillary Deposition Test 1

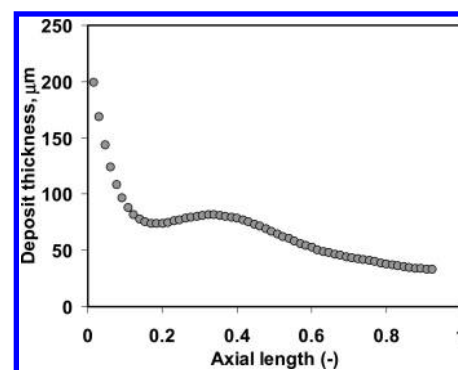
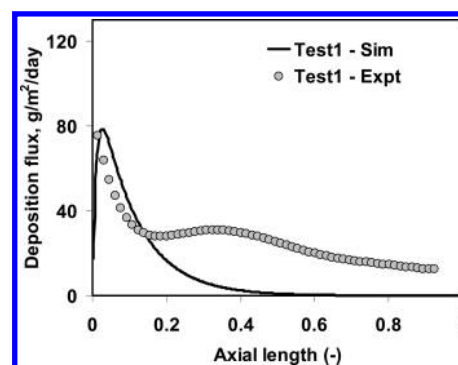
| deposition test 1 | |
|----------------------|-----------------|
| temp, °C | 70 |
| precipitant | C ₁₅ |
| oil/precipitant, v/v | 76:24 |
| pipe length, ft | 106 |
| diameter, in | 0.02 |
| flow rate, mL/h | 4.0 |
| flow time, h | 63.2 |

of asphaltenes at varying conditions from the thermodynamic module. Given the thermodynamic stability, along with kinetic and other operating parameters such as the length, diameter, and flow rate of the oil, the deposition module computes the deposition profile along the length of the pipeline or well bore. The kinetic constants can be determined by performing batch kinetic experiments if a sample of the oil used in the capillary deposition study is available. The deposition profiles predicted by the simulator can also be benchmarked against limited field data on deposit thickness, if available, and the simulator can then be used to predict the deposition thickness and the profile of the deposit along the well bore for different operating conditions.

RESULTS AND DISCUSSION

The ADEPT simulator, developed as described in the previous sections, has been used to predict asphaltene deposition profile on two different scales, viz., capillary-scale deposition experiments and field-scale deposition data. The simulator was first tested to predict the deposition profile on a capillary scale and then was further used for predictions of deposition in the well bore. As mentioned previously, two oil fields for which the asphaltene deposit profile was available were modeled thermodynamically. The thermodynamic model was then coupled with the deposition simulator to predict the deposition profile. In the following sections, analyses of the simulator predictions of lab-scale and field-scale asphaltene deposition profiles are discussed.

1. Benchmarking the ADEPT Simulator for the Capillary Deposition Experiment. Asphaltene deposition study using a capillary tube with crude oil M1 and precipitant penta-decane (C₁₅) was conducted according to the procedure described in the experimental section (test 1). The SARA (saturates, aromatics and resins, asphaltene) analysis data and the other properties of

**Figure 4.** Asphaltene deposit thickness profile along the dimensionless axial length of the capillary pipe.**Figure 5.** Comparison of experimentally observed asphaltene deposition flux along the dimensionless axial length of capillary pipe against simulation predictions for operating conditions of test 1. (Table 2 and Table 3).**Table 3. Kinetic Parameters Used for the Prediction of Asphaltene Deposition Profile in Capillary Deposition Test 1 and Test 2**

| kinetic parameters—test 1 and test 2 | |
|--------------------------------------|-----------------------|
| k_p , /sec | 1.45×10^{-3} |
| k_{ag} , /sec | 5.07×10^{-3} |
| k_d , /sec | 1.31×10^{-2} |

the oil such as density are presented in Table 1. The operating parameters such as the length and diameter of the pipe and the flow rate of the oil—precipitant mixture are reported in Table 2. The asphaltene deposition profile along the axial length of the capillary tube, for this set of operating conditions, was obtained by the method described in the experimental section and is shown in Figure 4. The deposition thickness profile shows that the magnitude of asphaltene deposition is the maximum at the entrance of the tube as a result of the maximum concentration driving force at this point. The deposition decreases along the axial length of the tube as the amount of asphaltenes in the flowing mixture decreases.

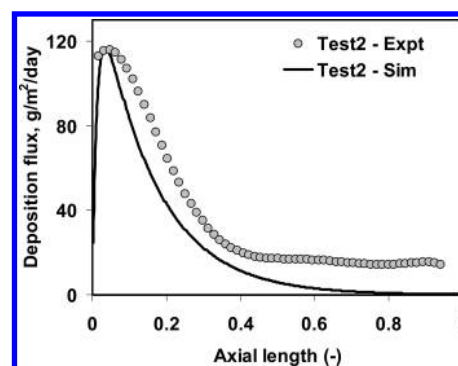
The thickness data obtained were converted to deposition flux (deposition flux = thickness \times surface area $\times \rho_{\text{solid}}$ /surface area) and are shown in Figure 5 as the filled symbols ($\rho_{\text{solid}} \sim 1 \text{ g/cm}^3$). With this set of operating conditions, as mentioned in Table 2, the deposition simulator was used to predict the deposition

Table 4. Experimental Operating Conditions Set for Capillary Deposition Test 2

| deposition test 2 | |
|----------------------|-----------------|
| temp, °C | 70 |
| precipitant | C ₁₅ |
| oil/precipitant, v/v | 76:24 |
| pipe length, ft | 105 |
| diameter, in | 0.03 |
| flow rate, mL/h | 11.7 |
| flow time, h | 35.9 |

profile in the capillary tube. The dispersion coefficient was calculated using eq 4. With this dispersion coefficient value, the operating conditions specified in Table 2, and the kinetic parameters as mentioned in Table 3, the simulator predictions were obtained and are shown in Figure 5. The kinetic parameters were obtained by matching the peak of the deposition flux obtained by simulations with the experimental observations. In the capillary experiments discussed in this paper, the mixture of oil–precipitant that is at the onset conditions is continuously pumped into the capillary tube. The system is maintained at constant temperature, and the pressure variation is not very significant along the capillary length. Hence, the only other factor that can affect the phase stability of asphaltene is the concentration of asphaltene in the mixture. Through phase behavior calculations, it has been observed that the solubility of asphaltene is not a very strong function of asphaltene concentration, but it is affected strongly by pressure and temperature variations. Hence, during the application of the simulator to study capillary deposition experiments, the solubility of asphaltene in the oil phase was assumed to be constant all along the length of the capillary. We can see that the simulator is able to sufficiently describe the experimentally observed deposition profile near the entrance of the tube. However, the simulator prediction deviates from the experimental observation toward the exit of the tube. The simulator predicts a cessation of deposition phenomenon after a certain distance downstream of the pipe entrance as a result of the exhaustion of asphaltenes from the flowing mixture, while the experiments show that the deposition attains a steady deposit thickness along the axial length. It should be recalled that the precipitation kinetics assumed in this work currently is a simple first order kinetics, which may not be sufficient to describe the precipitation of the polydisperse asphaltenes. Different fractions of asphaltenes may precipitate out at different rates, causing the presence of deposit even toward the exit of the pipe. Also, phenomenon such as the removal of deposit and subsequent deposition at other locations of the pipe are not considered in the present model, which may also explain the presence of deposit around the exit of the pipe. A further rigorous experimental evaluation is necessary to support and add these additional components into the model. Hence, inclusion of these factors is not considered in this model but is definitely of future interest. Nevertheless, the ability of the ADEPT simulator to evaluate the location and magnitude of the maximum deposit thickness is a crucial piece of information to possess for flow assurance risk assessment and decision making.

2. Assessment and Validation of the ADEPT Simulator: Prediction at Different Operating Conditions. The same oil–precipitant mixture described in the previous section was again used to perform another capillary deposition experiment

**Figure 6.** Comparison of experimentally observed asphaltene deposition flux along the dimensionless axial length of capillary pipe against simulation predictions for the operating conditions of test 2.

with different operating conditions (test 2). The purpose of test 2 was to understand the effect of change in operating conditions on the asphaltene deposition profile in the capillary tube. The tube used was larger in diameter, and the experiment was conducted at a higher flow rate of the oil–precipitant mixture. The conditions are summarized in Table 4, and the asphaltene deposition flux profile along the axial length of the capillary tube is shown in Figure 6 (solid data points). This experimental data set was then used to test the prediction capability of the deposition simulator. Because the same oil–precipitant mixture was used in this case and the temperature and the other conditions were all maintained the same, the same kinetic parameters described in Table 3 were used for the prediction. With the new operating conditions (Table 4), the deposition simulator was run, and the predictions are compared against the experimental observations in Figure 6 (continuous line). It is evident from the figure that the simulator predictions match well with the experimental observations. It can be deduced that, for a larger diameter tube and when operating the system with a higher flow rate, a relatively higher amount of asphaltene deposition is observed, as compared to the deposition profile in a thinner tube and when operating at lower flow rates (cf. Figures 5 and 6). A larger diameter tube and higher flow rate result in a higher amount of asphaltene mass flux into the tube, allowing more asphaltenes to be precipitated and available for deposition, and thus causes an increase in the deposition. A comparison of the shapes of the deposition flux profile obtained for test 1 and test 2 also shows that the deposition profile becomes broader and the deposition peak shifts axially more toward the exit of the tube for test 2, as compared to sharp peak observed for test 1. An increase in the diameter and flow rate of the tube increases the dispersion coefficient (eq 4), which can cause peak broadening. Also, when the flow rate is high, the fluid residence time decreases and the precipitated asphaltene that is available for deposition is carried away by the flow for longer distances before finally depositing, making the deposition peak much broader than that of test 1. In test 1, the low flow rates and longer residence time ensure that the precipitated mass is deposited, and hence, the sharp peak is observed.

Also, it can be seen from Figure 6 that the ADEPT simulator predicts the increase in deposition flux and the change in the shape of the deposition flux profile with an increase in flow rate and use of larger diameter tube, as experimentally observed. However, similar to the case of the comparison of simulator predictions with the test 1 results, it can be seen that the simulator does not predict the presence of a steady deposition

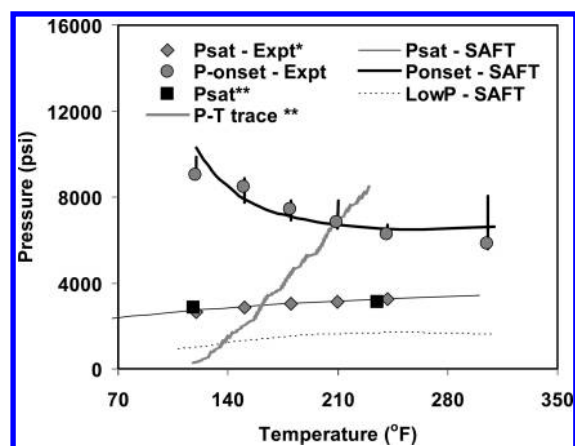


Figure 7. Phase behavior of asphaltene in oil for different pressure and temperature conditions for the oil from Kuwait's Marrat oil well (*, data reported;²⁵ **, data from Chevron²⁶).

flux toward the exit of the pipe. Nevertheless, in spite of these discrepancies, the ADEPT simulator has been able to capture the overall trends in the deposition profiles with changes in operating conditions very well.

3. ADEPT Simulator for Field Case Studies. In the previous section, the ADEPT simulator was tested to match the experimental deposition trends for capillary tube experiments. In this section, the application of the ADEPT simulator to predict asphaltene deposition observed in field cases is discussed. An accurate prediction of the deposit requires reliable information about the thermodynamic and physical properties of the oil for an efficient thermodynamic characterization. A reliable description of the operating conditions, such as flow rate, length and diameter of the well bore, and pressure and temperature variations inside the well bore, is also required. The kinetics of precipitation, aggregation, and deposition are also required, and most importantly, the deposit thickness measurements should be available to test the prediction capability of the simulator. Unfortunately, review of the data available in the literature revealed that there is no oil field with all this data measured and reported. With this data limitation, the ADEPT simulator was used to predict asphaltene deposition for two oil field cases for which deposit profile measurements and sufficient thermodynamic and physical properties were available for the relatively accurate thermodynamic characterization of the oil.

3.1. Case I: Kuwait's Marrat Oil Well. Asphaltene deposit caliper measurements for one of the Marrat oil wells in the oil fields of South Kuwait were reported in the publication by Kabir et al.²⁴ The literature review indicated the availability of a few thermodynamic and physical properties of oil from the same field in another publication.²⁵ With this available information and with more data available from the internal database of Chevron,²⁶ it was possible to apply the deposition simulator to predict the deposition in the oil well of this field.

3.1.1. Thermodynamic Characterization and Modeling of the Live Oil. As described in the section on the structure of the deposition simulator, one of the first steps before using the deposition simulator is to perform the thermodynamic characterization of the live oil in order to obtain a sufficiently adequate thermodynamic model that describes the phase behavior of asphaltenes in the live oil, with variation of pressure and temperature along the depths of the well bore, before we use the PC

Table 5. Well Bore Operating Conditions for the Kuwait's Marrat Oil Field.²⁴

| Kuwait field well bore parameters | |
|-----------------------------------|--------|
| well bore depth, ft | 15 000 |
| tube diameter, in. | 2.75 |
| flow rate, STB/day | 5000 |

SAFT equation of state to thermodynamically model the oil through the commercially available software Multiflash by Infocchem and VLXE. The live oil composition for this oil-field was obtained from the internal database of Chevron.²⁶ The publication by Kabir et al.²⁵ describes the phase behavior of oil from one of the oil wells in the same field. The thermodynamic properties such as saturation pressure and asphaltene onset pressures for different temperatures and the dead oil compositional information (SARA) were obtained from this publication.²⁵ These properties are required for the characterization procedure and PC SAFT parameter estimation. The details of the characterization procedure and PC SAFT parameter estimation can be obtained from the publications of Ting et al.⁸ and Gonzalez et al.²²

The oil density was reported to be about 36–40° API²⁴ (American Petroleum Institute). The oil characterization was performed to match this density range, and the PC SAFT prediction obtained was 37.7° API. Figure 7 shows the effect of temperature on the saturation pressure of the oil. The solid diamond data points in Figure 7 represent the experimentally measured saturation pressure points obtained from Kabir et al.²⁵ The two black filled square data points in Figure 7 are the saturation pressure values obtained from Chevron internal database,²⁶ indicating the similarity of the oils. The gray solid line in Figure 7 is the PC SAFT prediction of the saturation pressure for different temperatures, and it is noticeable that PC SAFT predictions match very well with the experimental measurements. The black filled circle data points with error bars represent the experimentally measured asphaltene onset pressure for different temperatures. The thick continuous line represents the PC SAFT simulation prediction. When compared to the reported onset values, the PC SAFT predictions match the experimental data very well. The well bore operating conditions are shown by the PT trace reported in the Chevron internal database.²⁶ The thin broken line represents the PC SAFT prediction of the asphaltene lower pressure onset curve. The region between the asphaltene onset pressure curve and the lower pressure curve constitutes the asphaltene precipitation region. Above this region, the oil is stable in terms of asphaltene. As the oil flows up the well bore, the pressure and temperature drop, as seen from the PT trace, and the oil enters the precipitation zone, where the asphaltene starts phase-separating out of the oil. This phenomenon continues until the saturation pressure curve, after which the light components in the oil start phase-separating out of the oil. The removal of these light components, which are themselves good precipitating agents of asphaltenes, makes the oil a better solvent for asphaltenes, and hence, below the lower pressure curve, the asphaltenes again become stable in oil. The pressure and temperature data were correlated to the well bore depth, and this information was used to calculate the thermodynamic stability of asphaltene in oil along the well bore depth. This is critical input data for the deposition simulator.

3.1.2. ADEPT Simulator Predictions. The operating conditions of the well bore such as the length and diameter of the well

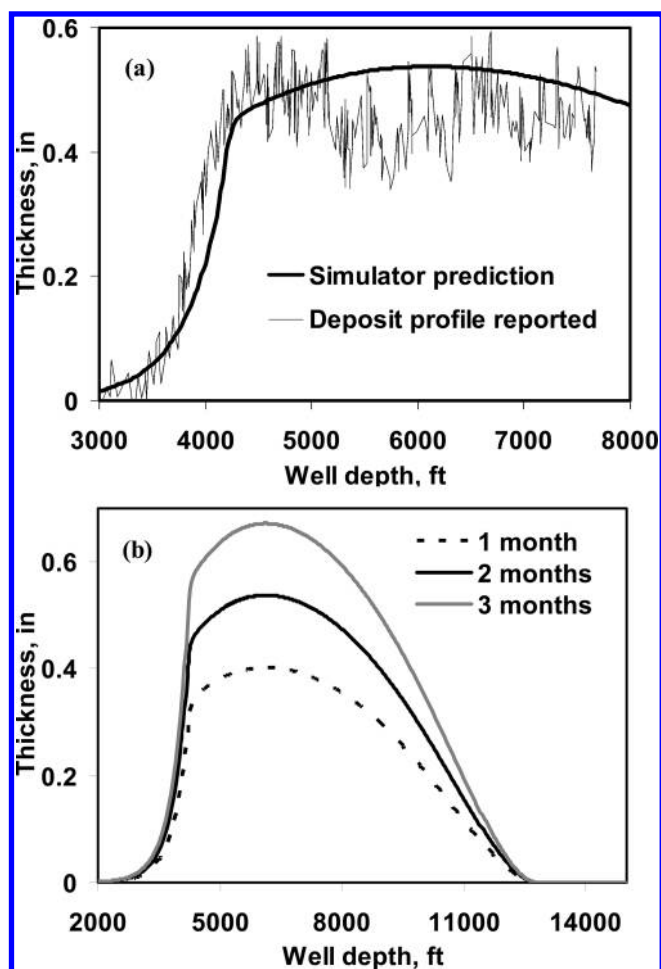


Figure 8. Asphaltene deposition profile along the axial length/depth of the well bore for the Marrat oil well: (a) comparison of simulator calculations against those reported²⁴ and (b) simulator predictions for varying duration of deposition.

Table 6. Kinetic Parameters Used in the Simulation Prediction of Asphaltene Deposition in the Well of Kuwait's Marrat Oil Field

| Kuwait field kinetic parameters | |
|---------------------------------|----------------------|
| k_p , /sec | 1.8×10^{-3} |
| k_{ag} , /sec | 1.8×10^{-3} |
| k_d , /sec | 1.5×10^{-5} |

bore and the flow rate of the oil are reported in Table 5.²⁵ Figure 8a shows the reported deposit profile measurement data along the well bore depth²⁵, as shown by the thin gray line. In the 15 000 ft deep well bore, the deposit seems to appear somewhere after 8000 ft depth and terminates before 4000 ft. The thickness of the deposit is about 0.5 in. The solid thick line passing through these field data points is the deposition prediction obtained with the ADEPT simulator with kinetic parameters listed in Table 6. The deposit thickness was matched by considering a time duration of 2 months for the deposit to form. We can see that, with proper choice of kinetic parameters, the deposition simulator, along with the thermodynamic model, is able to predict the deposit profile both qualitatively and quantitatively and the predictions match

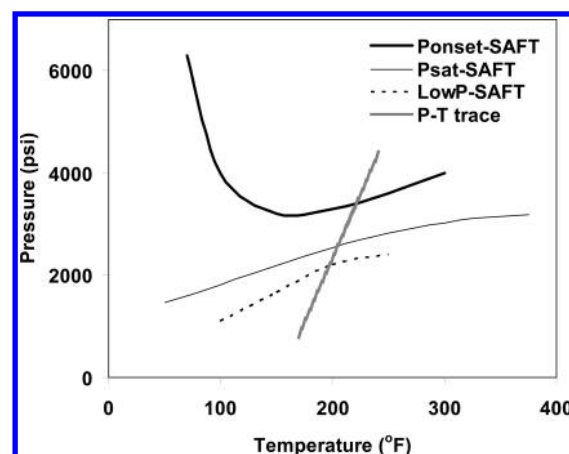


Figure 9. Phase behavior of asphaltenes in oil for different pressure and temperature conditions for the oil from Hassi-Messaoud field.

very well with the field observations. The deposition profile starts at a depth of ~10 000 ft, following an almost straight profile and starts decreasing around 4000 ft (Figure 8b). Below the bubble point, the asphaltene precipitating components start liberating out of the oil, which causes the oil to be a better solvent for asphaltenes, and hence, we see a cessation of the deposit. The deposition profiles for durations of one and three months are also shown in Figure 8b. Because the kinetic parameters were not known for this oil, the values for precipitation and aggregation kinetic constants obtained from the capillary deposition experiments were chosen as reference values, and these parameters were then slightly adjusted to match the shape of the deposition profile. It should be noted that the parameter values are within the same order of magnitude. The kinetic constant for deposition was adjusted to match the deposit thickness for the duration of deposition considered (2 months). Sensitivity analyses demonstrating the effect of these three kinetic parameters on the shape and magnitude of the deposition profile is shown in the Appendix.

3.2. Case 2: Hassi-Messaoud Oil Field. The Hassi-Messaoud oil field has been one of the few fields referenced several times in the literature as an example to demonstrate the problems caused by asphaltene deposition in the production tubing. The publication by Haskett and Tartera²⁷ gives a detailed description of this problem and also describes a remediation technique to lessen the production loss due to asphaltene deposition in the well bore. This publication also provides information about the asphaltene deposition profiles measured in a few of the wells in this field. As compared to the previous case, the amount of information required for an accurate thermodynamic characterization of the live oil was not complete. Nevertheless, this field case is an excellent benchmarking example to validate the newly developed ADEPT simulator.

3.2.1. Thermodynamic Modeling of the Live Oil. As mentioned in previous subsection, an accurate thermodynamic characterization and validation of the model for this live oil was difficult to conduct because of the insufficient data available. Data such as the live oil composition and the density of the oil were obtained from Haskett and Tartera.²⁷ With this information and with SARA data from Minssiux,²⁸ the oil was thermodynamically modeled with the PC SAFT equation of state, as described earlier. The developed thermodynamic model was validated against data points available from the internal database of Chevron. The PC SAFT parameters for asphaltenes previously reported²² were used. The phase behavior of asphaltene obtained by using PC SAFT is

Table 7. Operating²⁷ and Kinetic Parameters Used for the Prediction of Asphaltene Deposition in Hassi-Messaoud Oil Field Well

| Hassi-Messaoud field parameters | |
|---------------------------------|----------------------|
| well bore depth, ft | 11 000 |
| tube diameter, in. | 4.5 |
| flow rate, STB/day | 10 000 |
| k_p , /sec | 9.0×10^{-2} |
| k_{ag} , /sec | 9.0×10^{-3} |
| k_d , /sec | 3.9×10^{-3} |

described in Figure 9. The thermodynamic model was characterized to match the density predictions of 41.38° API, as reported.²⁷ The thick dark line constitutes the asphaltene precipitation onset pressure curve, while the thin line is the saturation pressure curve for the varying temperatures. We can see that, within the temperature range 250–150 °F, the saturation pressure falls between 2800–2100 psi. The thermodynamic model was characterized to match this range of saturation pressure that was reported in the paper by Haskett and Tartera.²⁷ The dashed line in Figure 9 comprises the lower onset pressure values for asphaltene phase separation. As described in the previous field case example, the region between the upper thick curve and the dashed curve represents the asphaltene precipitation zone. This thermodynamic model was then used to predict the phase behavior of asphaltenes in the live oil as the oil flows up through the well bore.

3.2.2. Deposition Simulator Prediction. One of the operating data sets described in ref 27 was used in the deposition simulator. The flow rate of the oil, the diameter of the tubing, and the length of the well bore are given in Table 7. Information about the pressure and temperature variations along the well bore was not available; however, it was mentioned that the temperature of the top of the deposit was estimated to lie in the range 240.8–168.8 °F, indicating that the location of the deposits varied from sometimes occurring as high as near the surface to sometimes occurring deep down the well bore. Hence, an approximate temperature profile that varied linearly in the range of temperature was assumed for the simulation. The temperature profiles are typically nonlinear in well bores; however, because of the lack of data, at this point, this assumption was made. In the case of the pressure variation, only the well head pressure was available (~780 psi). To obtain the pressure variation, one of the deposit profile measurement data that was mentioned in the paper was used as the reference, and for this case, it was seen that the deposit started at depth of 7700 ft. Hence, by assuming a pressure value equivalent to the asphaltene onset pressure at this depth and with the well head pressure at the uppermost point of the well bore, the rest of the linear pressure variation was calculated. The thick gray line represents the pressure temperature operating points as the oil flows up the well bore. The thermodynamic model was then used to describe the phase behavior of the oil along the well bore, and this information was given as input to the deposition simulator.

The asphaltene deposition profile along the well bore used as a reference for this simulation and that was reported in Haskett and Tartera²⁷ is shown in Figure 10a. The deposit is around 0.6 in. thick and spreads for around 1000 ft, starting at ~7700 ft and ending at ~6700 ft. Using the operating and kinetic parameters given in Table 7 and by using the thermodynamic model described in the previous subsection, the deposition simulator predicts a deposition profile, as shown in Figure 10b. The kinetic

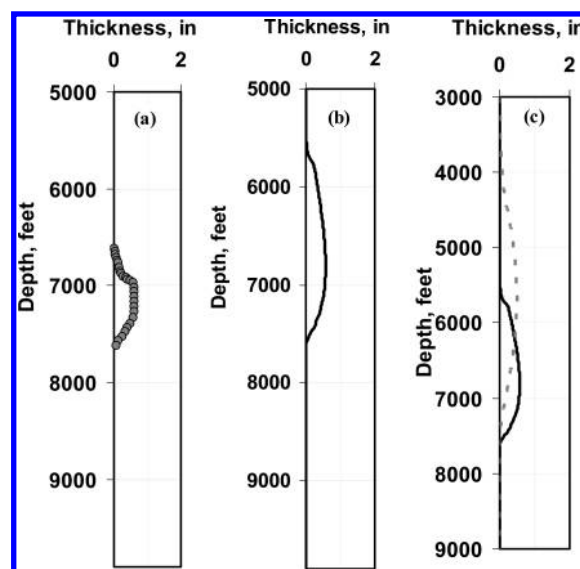


Figure 10. Comparison of the asphaltene deposition profile along the axial length/depth of the well bore reported in ref 27 (a) against those calculated by the ADEPT simulator (b) and ADEPT simulator predictions with kinetic parameters used for Marrat oil well (c) (dashed line).

parameters were chosen using the same methodology described for the previous field case. In this case, it is seen that, to obtain the narrow spread of the deposit, the precipitation kinetic constant chosen is much higher compared to that in the previous field case. The deposition profile, with k_p and k_{ag} used for the previous field case is shown in Figure 10c.

It can be seen that the simulator is able to match the thickness and the shape profile of the deposit for a period of 25 days, which is the average of the time interval reported in the paper. However, the spread of the deposit predicted by the simulator seems to be broader by ~1000 ft than what has been reported (Figure 10a). Haskett and Tartera²⁷ have also reported in their publication that, initially, as the deposition process starts, the deposits are typically long, spreading over ~2000 ft. These deposits, as they grow in thickness, generate increasing frictional loss in the fluid flowing past the deposit, causing the saturation pressure point to move down the well bore with time. Because the deposit ceases to form above the saturation pressure point, the deposit becomes shorter as it thickens. The model used in the simulator currently does not take into consideration how the growing deposit affects the deposition flux or the effect of changes in flow profiles caused by a growing deposit on the deposition flux. This could be one of the reasons for an over prediction of the deposit spread with the deposition simulator. Also, the spread of the deposit is very strongly affected by the asphaltene precipitation zone, which, in turn, is strongly dependent on the pressure–temperature conditions, and hence, an accurate representation of the pressure–temperature variation, which is possible with more reliable input data, could possibly improve the simulator predictions. Nevertheless, it is important to note that the simulator is able to qualitatively and quantitatively describe the asphaltene deposition in this field case.

CONCLUSIONS

Asphaltene deposition in the flow lines and well tubings cause significant production loss requiring the ability to forecast the

possibility, location, and magnitude of deposition in these systems. This study elucidates the development and application of the ADEPT simulator that can be used for the prediction of asphaltene deposition in well bores and pipelines. A capillary scale deposition apparatus, reported previously, can be used to provide estimates of the kinetic parameters required in the asphaltene deposition simulator. The model discussed in this study was first benchmarked against capillary deposition experimental data and then used to predict change in capillary deposition profile when the experiment is conducted at different operating conditions for the same oil-precipitant mixture. The model predictions were in good agreement both qualitatively and quantitatively, with the change in the asphaltene deposition profile, as was observed experimentally.

The ADEPT simulator was then used for the prediction of asphaltene deposition in two field cases that have asphaltene deposition profiles along the length of the well bore tubing measured and reported in the literature. Thermodynamic modeling of the live oil was first performed by matching thermodynamic and physical property predictions with reported values in cases where these measurements were available. The thermodynamic model coupled with the deposition model was then used to study the deposition profile in the well bore tubing, as the pressure and temperature vary along the axial length of the well bore. A good match could be obtained between the field observation and the predictions made by simulator for a suitable set of kinetic parameters used in the model. The study demonstrates that the ADEPT simulator can be used to compute asphaltene deposition in the well bore.

It should be noted that the current version of the simulator does have limitations in capturing the entire physics of the deposition process for the capillary scale experiments. However, incorporation of these additional factors requires rigorous and systematic experimental observations which are currently unavailable and should be addressed in the future. As a result of the lack of these experimental measurements currently, the incorporation of these additional terms would just add the number of parameters that need to be tuned to match the experimental observations and hence was not considered in this work.

Nevertheless, as discussed previously, the simulator can be easily coupled with various multiphase flow simulators. This will enable the estimation of the extent of the deposition of asphaltenes due to changes in pressure and temperature conditions as the production continues or due to changes in other operating conditions (changes in well head pressure, flow rates, etc.). The simulator, once benchmarked for a particular oil field, can be used by engineers for quick sensitivity analyses against changes in the operating conditions, as well as to forecast and sketch out regions of possible asphaltene problems, enabling better flow assurance risk management practices.

APPENDIX

To understand the effect of the three kinetic parameters on the shape and magnitude of the asphaltene deposition profile, a sensitivity analysis involving these three parameters was performed. The operating conditions and the kinetic parameters used in the simulation of test 2, described earlier, was used as the base case, and each kinetic parameter was then varied to understand the effect of that parameter on the deposition profile. The effect of k_p , k_{ag} , and k_d on the asphaltene deposition profile is shown in Figures A1, A2, and A3, respectively.

It can be seen that, in case of capillary deposition experiment, the value of k_p has a very significant impact on the shape and

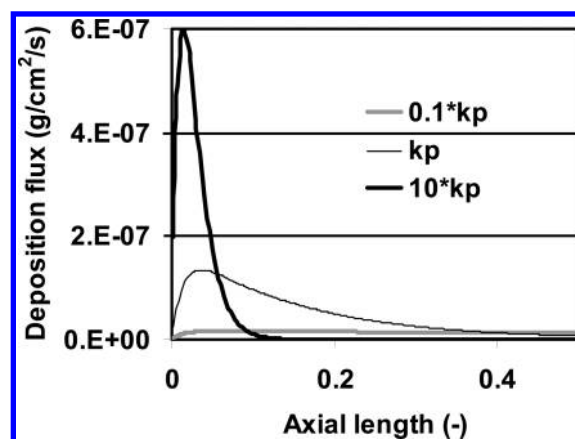


Figure A1. Effect of precipitation kinetic constant k_p on the deposition profile.

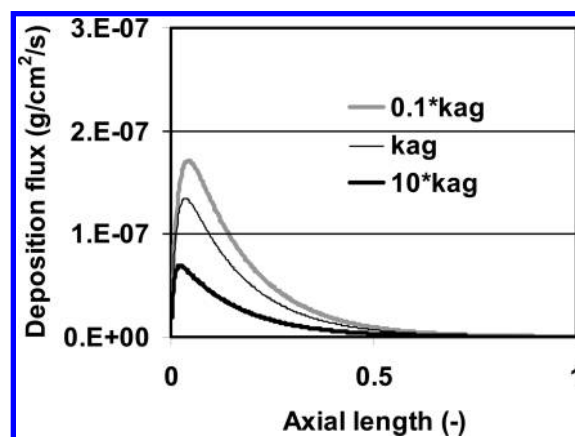


Figure A2. Effect of aggregation kinetic constant k_{ag} on the deposition profile.

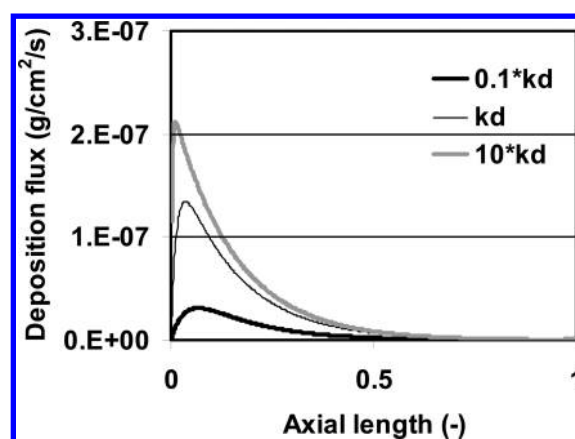


Figure A3. Effect of deposition kinetic constant k_d on the deposition profile.

magnitude of deposition flux, as compared to those of k_{ag} and k_d . For low values of k_p , the deposition profile assumes a very flat profile along the axial length, and at higher values of k_p , the deposition profile has a very sharp peak. Similar effects are

observed for increases and decreases in the value of k_d ; as expected, a reverse trend is observed for change in k_{ag}

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ACKNOWLEDGMENT

The authors thank Deepstar consortium for granting the approval to publish this manuscript. A.S.K. and W.G.C. acknowledge financial support from the Deepstar consortium.

NOMENCLATURE

C =concentration of precipitated (phase separated) asphaltene particles, g/mL.
 C =dimensionless concentration of precipitated (phase separated) asphaltene particles.
 C_0 =initial concentration of asphaltene solubilized in the oil phase, g/mL.
 C_{eq} =dimensionless maximum concentration of asphaltene at equilibrium in the oil phase.
 C_f =dimensionless concentration of asphaltene solubilized in oil phase.
 D =axial dispersion coefficient, cm^2/s .
 Da_{ag} =aggregation Damkohler number.
 Da_d =deposition Damkohler number.
 Da_p =precipitation Damkohler number.
 D_m =particle diffusivity, cm^2/s .
 D_p =diameter of pipe, cm.
 k_{ag} =aggregation kinetic constant, /s.
 k_d =deposition kinetic constant, /s.
 k_{diss} =kinetics of dissolution factor.
 k_p =precipitation kinetic constant, /s.
 L =axial length of the pipe/well bore, ft, cm.
 Pe =Peclet number
 R =radius of the pipe/well bore, in., cm.
 Re =Reynolds number.
 t =time, s.
 \bar{t} =residence time in a pipe.
 V_z =average axial velocity of the oil flowing through pipe/well bore, cm/s.
 z =axial length, cm.
 Z =dimensionless axial length.
 θ =dimensionless time.

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