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Investigation of Asphaltene Deposition and Precipitation in Production Tubing

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Abstract

Asphaltenes are complex molecular entities, which together with resins, aromatic hydrocarbons and saturates forms the crude oil. Asphaltenes and resins are in the thermodynamic equilibrium at static reservoir condition. However, asphaltene can precipitate due to changes in thermodynamic condition. Asphaltene deposition in production tubings has been an outstanding problem with wide economic impact on the oil industry. Meanwhile, the use of real-time tools to monitor depositions along the well is of great difficulty. In this work, the asphaltene precipitation region in a single phase flow wellbore is predicted for an oil well of the Iranian oil field. Then, asphaltene deposition thickness along the well is predicted for three time intervals. The simulation results indicated that asphaltene thickness exceeded more than 50% of tubing radius; therefore, a reduction in flow rate, an increase in pressure drop and tubing blockage are expected. Moreover, it is shown the deposits thickness along the wellbore has approximately a skew normal distribution shape, which could be the result of increases in velocity and excess pressure drop.

Keywords

Asphaltene Precipitation, Asphaltene Deposition, Wellbore, Production Decline

1. Introduction

Hydrocarbon crude oil is a complex mixture of hydrocarbon, hetero-atoms such as sulphur, oxygen and nitrogen as well as compounds containing metallic constituents particularly vanadium, nickel, iron and copper. The complexity of hydrocarbon fluid further increases due to the fact that its composition can vary not only with the location and the age of oil field but also with the depth of individual wells. Since petroleum comprises hundreds of molecular species, a simpler means of describing petroleum is in terms of four major fractions (based on

their solubility and polarity): 1) saturates, 2) aromatics, 3) resins and 4) asphaltenes; known as SARA fractions. Based on this classification method, asphaltenes are the heaviest and most polar fraction of petroleum. The asphaltenes and resins have similar molecular structure but as a result of solubility based fractionation scheme employed, resins are less polar, less aromatic and have lower molar mass than asphaltenes [1]. Structural studies indicate that the asphaltene and resin molecules have a similar molecular weight ranging from 500 to 1000 g/mol. Asphaltene, however, can form aggregates with molecular-weight distribution of 10^3 to 10^5. These aggregates are stabilized in solution by the resins and aromatics which act as peptizing agents. When this protective shield is removed by preferential dissolution of the resin into the fluid phase, asphaltene molecules start to flocculate and aggregate into large enough particles resulting in deposition [2]. Because asphaltenes are stabilized as colloidal particles peptized by resins, any action of a chemical, electrical, or mechanical nature that de-peptize these particles will lead to flocculation and precipitation. In production systems, changes in temperature, pressure and chemical composition of crudes, combined with streaming-potential effects in well tubing, affect asphaltene stability [2].

2. Asphaltene Precipitation

The term deposition has often been used to describe the precipitation process. It is important to clarify the difference between the two. While the precipitation is defined as the formation of a solid phase out of a liquid phase, deposition can be described as the formation and growth of a layer of the precipitated solid on a surface. Further, a necessary but not a sufficient condition for deposition is the precipitation of a solid phase from liquid solution. Moreover, whereas the precipitation is mainly a function of thermodynamic variables such as composition, pressure, and temperature, the deposition is also dependent on the flow hydrodynamics, heat and mass transfer, and solid-solid and surface-solid interactions [3].

2.1. Effect of Compositional Change

Asphaltene precipitation can occur during mixing of incompatible hydrocarbon fluids, miscible flooding, CO_2 flooding [4], gas lift operation using rich gases [5] [6] [7] and/or acidizing jobs. The addition of compounds with molecules that differ greatly from resins and asphaltene in terms of size and structure changes the solubility parameter [3].

2.2. Effect of Pressure Change

Asphaltene precipitation and deposition can also occur in oil-well tubing below the depth at which the oil becomes saturated. This phenomenon is largely ascribed to the different extents of compressibility of the light ends and the heavy components (e.g., resins and asphaltene) of the under-saturated crude. In fact, the relative volume fraction of the light ends within the liquid phase increases as the pressure of the under-saturated reservoir fluid approaches its bubble point.

Such an effect is similar to adding a low molar mass hydrocarbon (precipitant) to a crude oil causing asphaltene de-peptization. Heavy component content in the crude oil is the main factor for the precipitation and deposition of asphaltene in the reservoir and wellbore. However, saturate components fraction and resin concentration in the crude oil also influence asphaltene precipitation. Pressure and temperature variation also affect the amount of asphaltene precipitation, decreasing the fluid pressure until bubble point pressure increases asphaltene precipitation. However, decreasing the pressure to below the bubble point pressure decreases asphaltene precipitation. In fact, pressure reduction causes more expansion in the relative volume fraction of the light components with respect to heavy components. This behavior is similar to that of adding light hydrocarbon fraction in the fluid which destabilizes asphaltene. In contrast, below bubble point pressure, the stability of asphaltene in the fluid is increased. Decreasing pressure to below bubble point, light components are evaporated and the remaining fluid becomes more asphaltene soluble. The temperature effect on asphaltene formation is not well understood thus far. Some researchers suggest that increasing temperature enhances asphaltene precipitation. However, asphaltene precipitation decreases in a two-phase condition by increasing temperature as shown by Darabi *et al.* [8], since light components are evaporated and asphaltene solubility increases in the remaining fluid.

In the literature, there are several approaches for modeling asphaltene precipitation such as solid model, thermodynamic solubility model [9] [10] [11] [12] [13], thermodynamic colloidal model [14], and thermodynamic miscellization model [15]. In this work, we used solid model which can be described as below.

The solid model for asphaltene precipitation was proposed based on a single-component approach. In this approach, the precipitated asphaltene is considered as a pure solid phase while the hydrocarbon fluid phases are modeled with a cubic equation-of-state (e.g. Peng-Robinson EOS) and the fugacity of the solid phase which consists of a single component can be calculated using:

$$\ln f_s = \ln f_s^* \frac{\overline{v}_s \left(P - P^* \right)}{RT} \tag{1}$$

where f_s is the fugacity of solid at reservoir pressure, f_s^* is the reference solid fugacity at a reference pressure (P^*), $\overline{v}_s$ is the molar volume of the solid phase and P^* is the pressure at which the asphaltene just begins to precipitate from crude oil. The representation of the solid asphaltene precipitate as a multi-component solid phase was investigated by Thomas *et al.* as well. The new representation uses the solid-liquid model which was initially developed by Won [16] in order to study wax. The new model was found to be successful and also suggested some fields for further investigation and development including studying the behavior when the solvent concentration increases. MacMillan *et al.* [17] and Chung [18] also matched experimental data with the new multi-component solid model. The specification of large number of parameters is one of the main disadvantages of the multi-component solid model for the asphaltene precipitate [19].

2.3. Asphaltene Deposition

Asphaltene deposition in the tubing and surface facilities are the most common flow assurance issues during the production of hydrocarbon reservoirs. Applications of CO_2 and light hydrocarbon gas injection have also introduced additional issues to the asphaltene formation in the reservoirs. In fact, the presence of light components in the crude oil enhances destabilization of asphaltene. Thus, asphaltene precipitation and deposition is commonly observed not only in heavy oil reservoirs, but also in conventional oil reservoirs.

Thawer *et al.* [2] designed a high pressure flow experiment to simulate production condition because of asphaltene deposition problem in ULA Field production facilities. Their laboratory observations were made on the regimes of deposition as a function of decreasing pressure down to and below bubble-point of live crude oil samples. During the experiment, the pressure loss that occurs in the production tubing was simulated by flowing through a variable back-pressure valve and a variety of commercially available chemicals (aromatic solvents) was used to assess and rank in order of asphaltene dissolving efficiency, which none of the blended chemicals was technically better than pure toluene and xylene. They reported asphaltene precipitation occurrence at pressure above the fluid's saturation pressure and continued till fluid's saturation pressure. Below sample's saturation pressure, deposition seemed to be stopped as a result of combination of two effects, *i.e.* turbulence increasing the rate of erosion and higher crude solvency.

Takhar *et al.* [20] used several experimental techniques to determine the asphaltene stability of a crude oil. They reported crudes with a resin to asphaltene ratio tending to unity are more likely to suffer from asphaltene precipitation than those with a ratio less that unity. They introduced a model to calculate the phase behavior by using the critical properties of the individual pure or pseudo components. Therefore, the model was calibrated with two of BPX's North Sea fields and has been conclusively shown to predict asphaltene deposition regions in production facilities.

Escobedo and Mansoori [21] studied the mechanism of migration of suspended heavy organic particles towards the walls in oil producing wells and pipelines by analyzing the diffusional effect on the solid particle deposition during turbulent flow condition. They presented a new expression of the transport coefficient for particles with different dimensionless stopping distance and reported the transport coefficient decreases with increasing crude oil kinematic viscosity. They used the deposition data from aerosols (deposition rates for aluminum and iron particles in air) to verify their model.

Kocabas *et al.* [22] developed a comprehensive wellbore model with all adsorption and mechanical trapping of asphaltene. The wellbore model coupled the asphaltene adsorption model with a series of phenomenological models that are independently validated with experimental and field data. The coupled mathematical model predicted permeability damage due to mechanical trapping and adsorption accurately when compared with experimental results.

Kokal *et al.* [23] described the results of the study on oil samples of north Ghawar reservoir that started to show precipitation problem and ways to alleviate the deposition problem. They reported that the precipitation was linked to gas coning/cresting in the wells. In other words, the gas from the gas-cap titrates the produced oil and causes precipitation of asphaltenes that deposit in the wellbores. The data also indicated that the precipitation onset occurs at relatively low GORs.

A multiphase (oil/gas/asphaltene/water) multicomponent hydrodynamic model has been developed by Ramirez-Jaramillo *et al.* [24] to represent the phenomenon of asphaltene deposition in producing wells. The model is based on the assumption that asphaltene particles are thermodynamically formed at a given set of P-T-X conditions during the flow, and both molecular diffusion and shear removal are two competing mechanisms that affect the radial diffusion and consequent deposition of asphaltene particles for turbulent/laminar flows in a well. They reported that by decreasing the flow rate, the deposition layer shifts to higher depths, and vice versa. The mean width of the deposit increases slowly as the flow rate is varied, indicating that the growth rate of the deposit will remain constant independent of the flow rate. They also predicted the deposition profiles and location as a function of time.

Soulgani *et al.* [25] presented a new approach, based on PVT data, for thermodynamic modeling of asphaltene precipitation which has been combined with temperature and pressure of the wellbore to predict the depth of asphaltene precipitation. They used WINPROP to build a thermodynamic model of asphaltene precipitation. Then, the profile of pressure and temperature that has been measured by Production Logging Test (*i.e.* PLT) was combined with asphaltene precipitation curves that were generated by thermodynamic model [26] [27]. Then, they converted pressure to depth by using fluid gradient for predicting the precipitation depth. They reported asphaltene precipitation could be reduced by decreasing well head pressure or by increasing tubing size. Also increasing well flow rate causes an increase in precipitation interval in wellbore.

Vargas *et al.* [28] developed a simulation tool that simultaneously accounts for asphaltene precipitation, aggregation and deposition. They mentioned transport of asphaltenes in the wellbore may follow a multi-step process, including precipitation, aggregation, advection, and deposition. The rate of asphaltene precipitation was assumed to be proportional to the supersaturation degree of asphaltenes, which is defined as the difference between the actual concentration of asphaltenes dissolved in the oil and the concentration of asphaltene at equilibrium. For the case that supersaturation degree is zero, the system is right at the onset of asphaltene precipitation. They also used pseudo-first order reactions to model the aggregation and deposition stages and assumed constant diffusivity of asphaltene particles in a flow.

Eskin *et al.* [29] analyzed the deposition mechanism of asphaltene in pipelines based on the theoretical and experimental approach. They proposed that particle deposition on the tubing depends on particle inertia and the fluid viscosity. To

simulate asphaltene deposition, they used the special Couette device, in which the inner cylinder rotates and particles deposit on the outer wall to measure the mass of asphaltene deposits at the different times.

Shirdel [30] studied the phase behavior and dynamic aspect of asphaltene deposition. He presented an asphaltene precipitation and deposition model into a thermal, multiphase, multi-component wellbore simulator that can be coupled with a compositional reservoir simulator. In his wellbore model, he assumed N_c + 4 transport equation corresponding to N_c hydrocarbon components' mass conservation plus water, liquid momentum conservation, gas momentum conservation and mixture energy conservation.

Abouie *et al.* [31] compared the performance of PR and PC-SAFT EOSs in both static and dynamic modeling of asphaltene phase behavior. The static results showed that both EOSs are capable of regenerating the experimental data. They proposed tuning the Peng-Robinson model based on the static results of PC-SAFT modeling to improve the prediction accuracy. Abouie *et al.* [32] also implemented PC-SAFT EOS into a compositional wellbore simulator and predicted the asphaltene deposition profile in the wellbore.

In this work, for the sake of simplicity, we used the same approach as Nghiem *et al.* [33]. So the fugacity of heaviest component, which resides in the solid phase, is calculated directly and a routine Peng-Robinson flash calculation is performed to equilibrate the fugacity of components in gas, liquid and solid phase.

3. Results

This section presents a case study for asphaltene precipitation and deposition in wellbore. The available PVT data is collected from a wellbore in Iranian oilfield (Fahlian reservoir) as can be seen below in Table 1 and Table 2.

In addition, Table 3 and Table 4 present the reservoir and wellbore conditions of this field, respectively.

Figure 1 shows the sketch of the wellbore subjected to asphaltene deposition in the Iranian oilfield, which is prepared by PROSPER Software. As can be seen in the figure, the wellbore depth and tubing diameter are 4337.9 m (14232.2 ft.) and 4.89 in., respectively.

In addition, Figure 2 shows P-T phase diagram of fluid sample. Based on the reported bottom-hole pressure and temperature, a single phase flow condition is expected in entrance of wellbore.

3.1. Inspection of Asphaltene Precipitation

In this work, we used the same approach as Ngheim [33] to predict the amount of asphaltene precipitation. Therefore, WinProp Software is used to evaluate the possibility of asphaltene precipitation at several pressures and temperatures. For this study, we used Peng-Robinson EOS for thermodynamic calculation of Win-Prop [34] [35].

The last fraction of oil components (*i.e.* C36+) was split into two components. The first one which is C36A+ contains soluble asphaltene in oil and the other

Table 1. Reservoir fluid composition.

Component	Composition %
N_2	0.07
CO_2	2.26
H_2S	0.22
C1	50.81
C2	8.80
C3	5.73
IC_4	1.07
NC_4	2.94
IC_5	1.22
NC_5	1.78
C6	2.19
C7	2.33
C8	2.52
C9	2.09
C10	1.80
C11	1.34
C12	1.18
C13	1.02
C14	0.90
C15	0.86
C16	0.72
C17	0.60
C18	0.60
C19	0.56
C20	0.52
C21	0.47
C22	0.44
C23	0.40
C24	0.37
C25	0.34
C26	0.37
C27	0.32
C28	0.29
C29	0.33
C30	0.29
C31	0.30
C32	0.26
Component	Composition %
C33	0.23
C34	0.23
C35	0.21
C36+	1.02
Total	100
C36+ Properties	
Density (gr/cc)	0.93
MW	491.16

Table 2. PVT data.

P_b (psia)	4285
R_s (scf/STB) at reservoir condition	2115
B_o (rb/STB) at reservoir condition	1.6997
Viscosity (cP) at reservoir condition	0.2568
$\degree$API	44

Table 3. Reservoir conditions.

P_{res} (psia)	9206
T_{res} ($\degree$F)	305

Table 4. Flow condition in wellbore.

P_{bh} (psia)	7200
T_{bh} ($\degree$F)	290
Flow Rate (STBD)	4845
P_{wh} (psia)	3600
T_{wh} ($\degree$F)	140
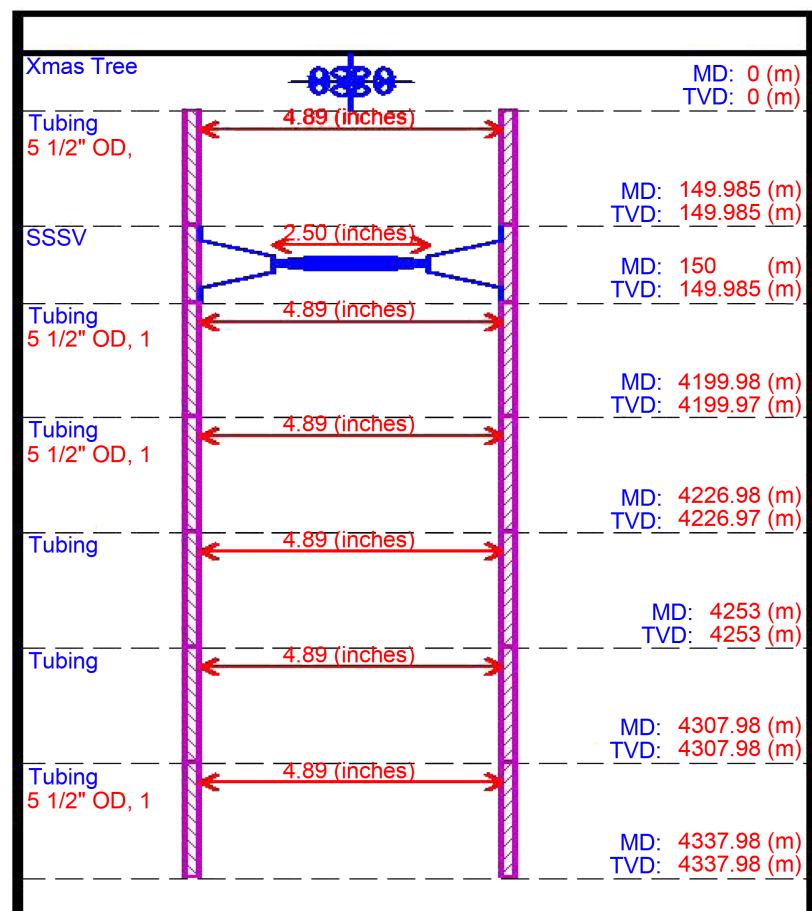
Figure 1. Sketch of case study wellbore.
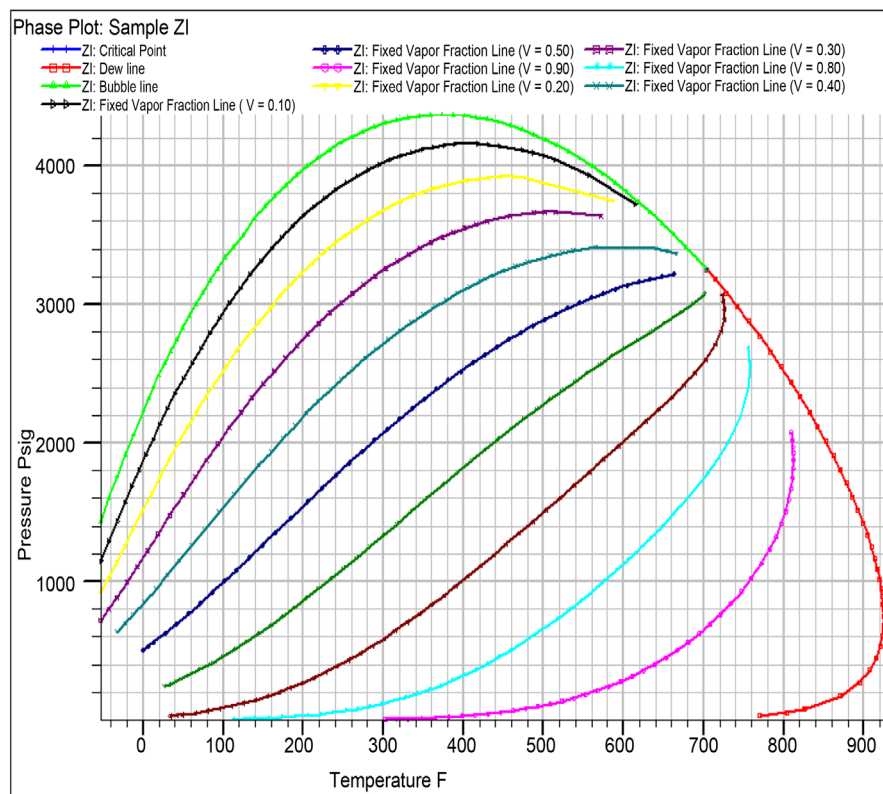
Figure 2. P-T phase diagram of reservoir oil.

one, C36B+, is the precipitating asphaltene component. These two components have identical critical properties and acentric factors, but different interaction coefficients with the light components. The precipitating component has larger interaction coefficients with the light components. Higher interaction coefficients indicate that the precipitating component is more incompatible with the light components and tends to precipitate more as the amount of light component in solution increases (CMG 2007).

The relation between asphaltene in solution and precipitated asphaltene can be found (CMG 2007) by Equation (2):

$$x_{asph}MW_{asph} = w_{asph}MW_{oil} \qquad (2)$$

where x_{asph} is the asphaltene mole fraction, MW_{asph} is the molecular weight of asphaltene, w_{asph} is the asphaltene weight fraction, and MW_{oil} is the molecular weight of the crude oil.

The molecular weight of residual oil is reported to be 136 lb/lbmol and the asphaltene weight percent in stock tank is reported to be 2.2%. Assuming molecular weight of asphaltene to be the same as molecular weight of C36+, *i.e.* 491.16 lb/lbmol, the mole fraction of precipitating asphaltene in the crude oil would be 0.609%.

Next, Peng-Robinson EOS was tuned with regression on critical pressure, critical temperature and volume shift parameters of the heavier Components. After tuning, molar volume of asphaltene was set to 0.645 lit/mol. Finally, the asphaltene precipitation envelope is plotted as shown in **Figure 3**. As can be ob-

served, the sample has a potential for asphaltene precipitation.

3.2. Detection of Deposition Region in Wellbore

In this work, PROSPER Software is used to build a profile of pressure and temperature in wellbore. Then, based on Soulgani *et al.* method [25], the P-T profile is combined with asphaltene deposition envelope to obtain the deposition region. **Figure 4** shows the asphaltene deposition envelope of the fluid sample.

Then by combining the P-T profile and asphaltene deposition envelope (shown in **Figure 5**), the asphaltene deposition region can be estimated. Also for the sake of simplicity, it is assumed the deposited asphatlenes only precipitate at the same region.
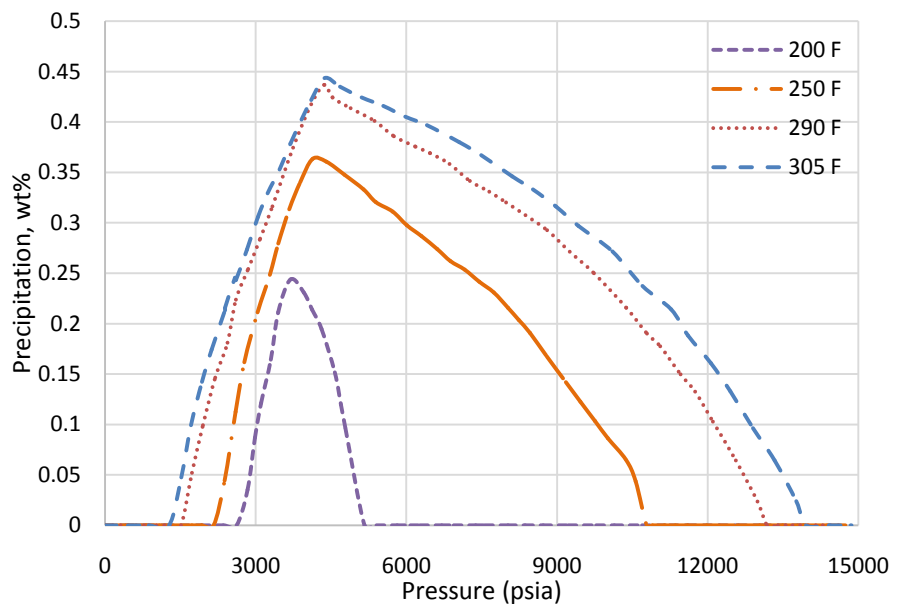
Figure 3. Asphaltene precipitation plot at different pressure and temperature.
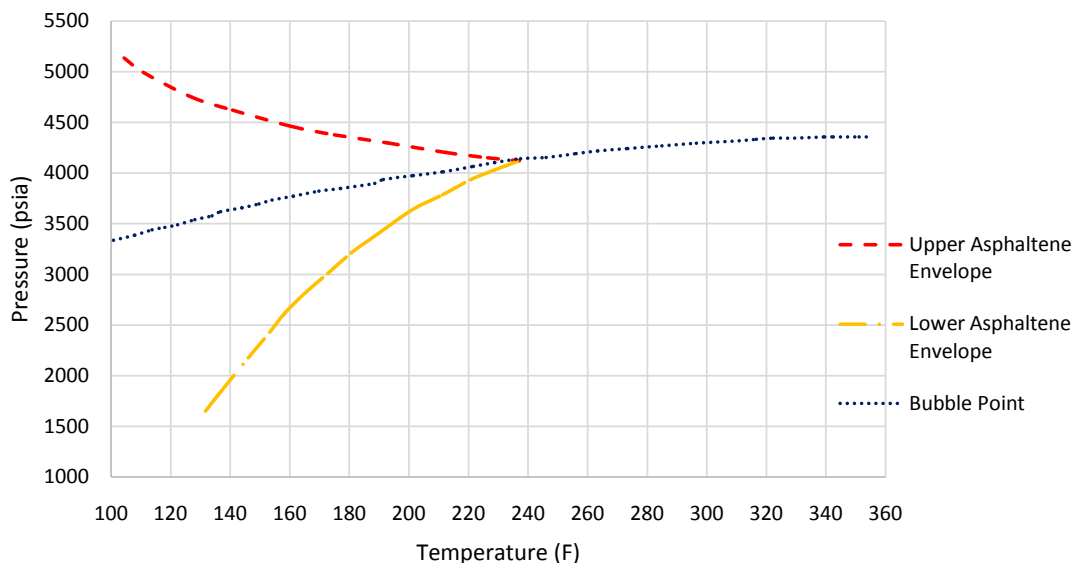
Figure 4. Asphaltene precipitation envelope.
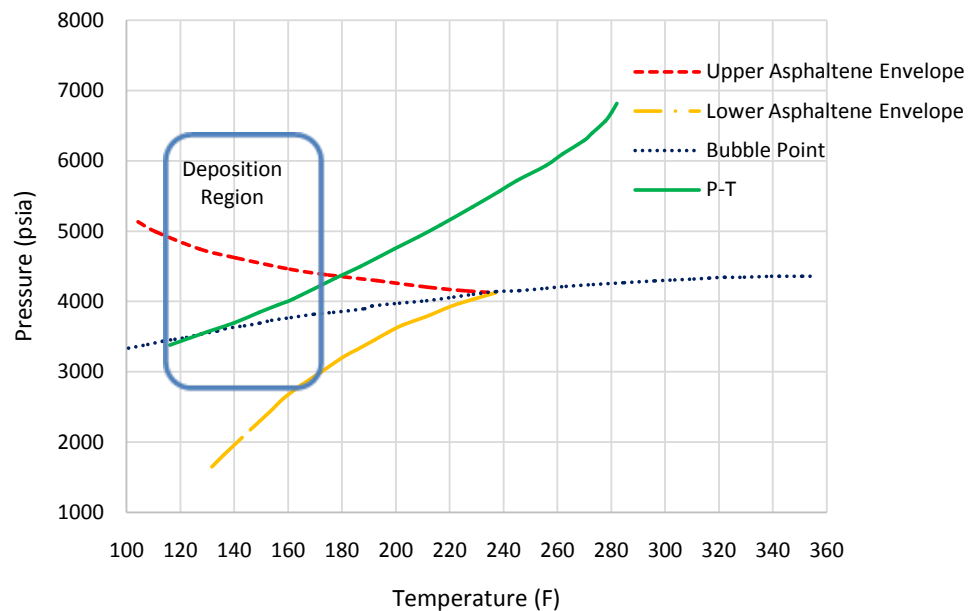
Figure 5. Combination of P-T profile and ADE in wellbore.

3.3. Asphaltene Deposition in the Wellbore

In the previous part, we determined the probable location of asphaltene deposition in the wellbore. Then, this region is normalized to unity and then discretized into 500 grid blocks. Then the precipitation and deposition calculations are performed based on Shirdel [30].

Figure 5 also illustrates that we have single phase flow in the wellbore and pressure and temperature of hydrocarbon mixture that enters into the deposition region, are 4340 psia and 180˚F, respectively. So the deposition region starts around the depth of 11,200 ft. In addition, the wellbore has an inner radius of 2.45 in., as it was shown in Figure 1. Productivity index of wellbore is set by PROSPER Software as shown in Figure 6. The reported flow rate is 4845 STBD or in other words, oil velocity is 4.1 ft³/s at the bottom hole. The average oil heat capacity is reported to be 0.53 BTU/˚F·lb and overall heat transfer coefficient is 5.4 BTU/Ft²·˚F·h.

Then, we run the simulation to evaluate the probability of asphaltene precipitation and deposition in the wellbore. Figures 7-9 show the predicted asphaltene deposition thickness after 30, 60 and 120 days, respectively. As shows in these figures, most of the deposition happens at the normalized depth of 0.3 and at the lower depth, lower deposition is observed. Note that the x-axis is in dimensionless form of the bottom-hole depth.

Figure 10 demonstrates the comparison of deposition thickness over time. Based on the results, deposition thickness exceeded half of the wellbore radius after 120 days. So, it is expected to have a reduction in flow rate and an increase in pressure drop in the wellbore.

Moreover, the simulation results show that the asphaltene deposition has approximately a skew normal distribution shape along the wellbore as a result of increase in velocity and pressure drop.
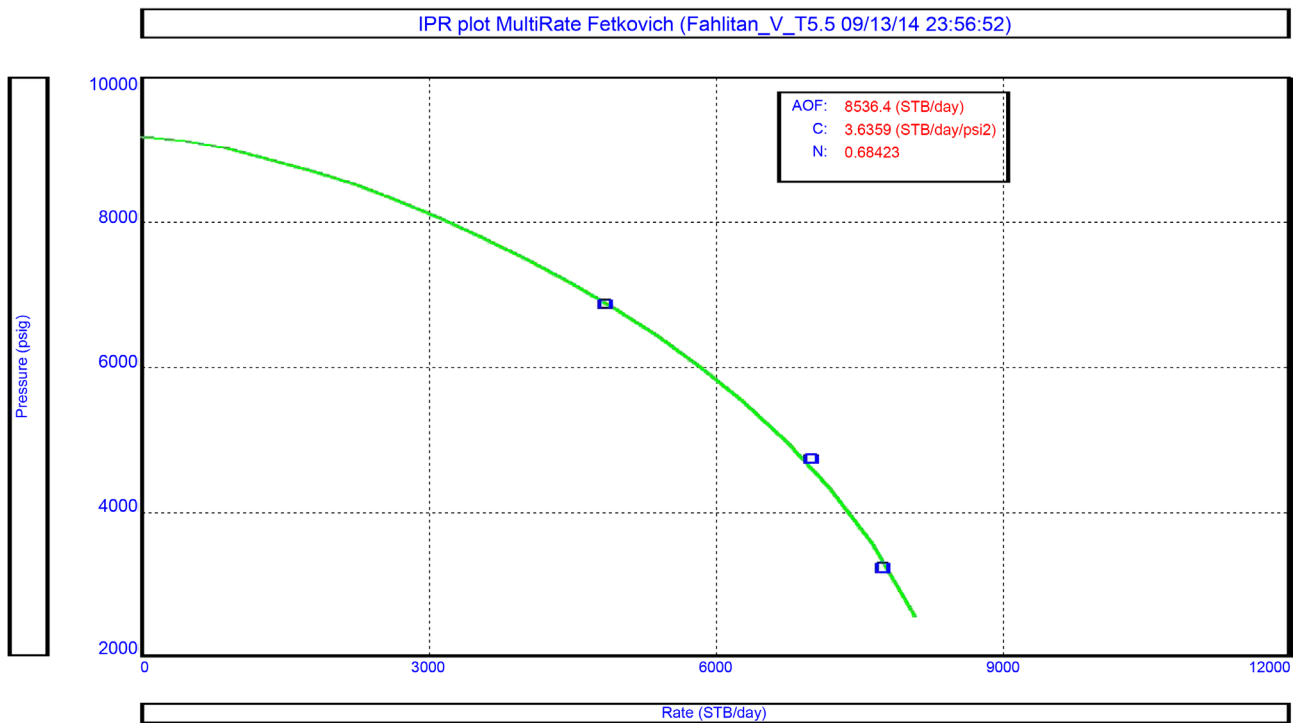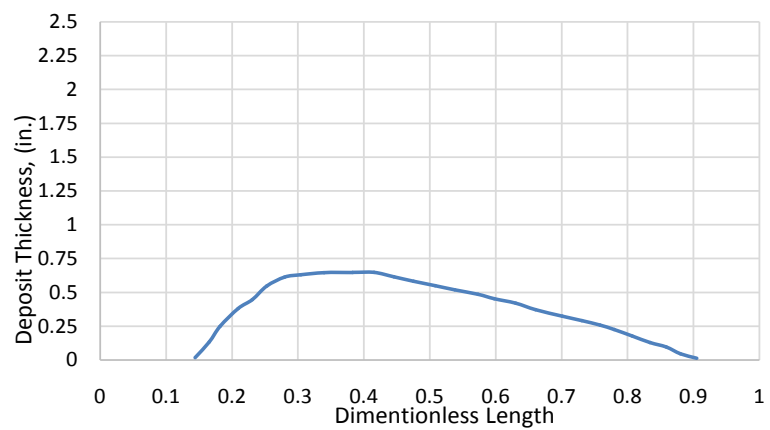
Figure 6. Productivity index of wellbore.

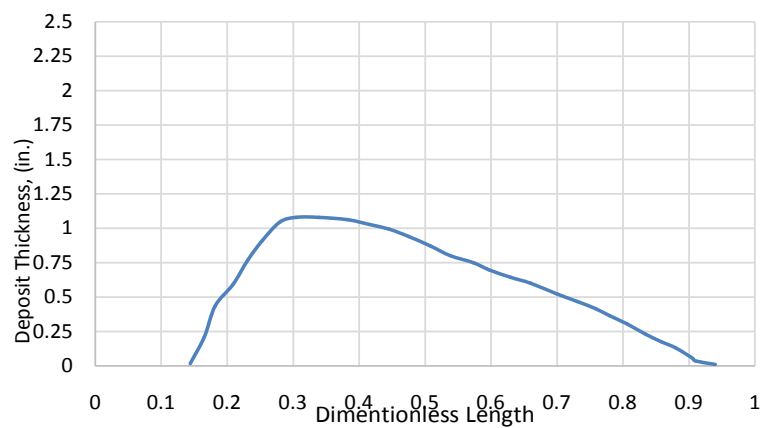**Figure 7.** Deposition thickness after 30 days.

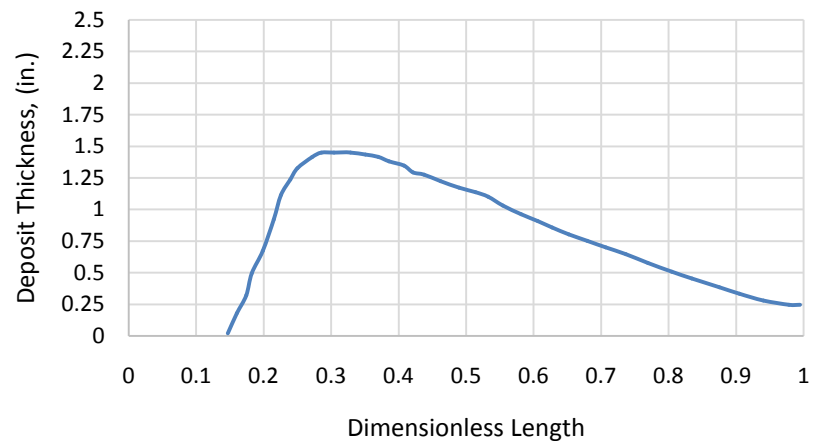**Figure 8.** Deposition thickness after 60 days.

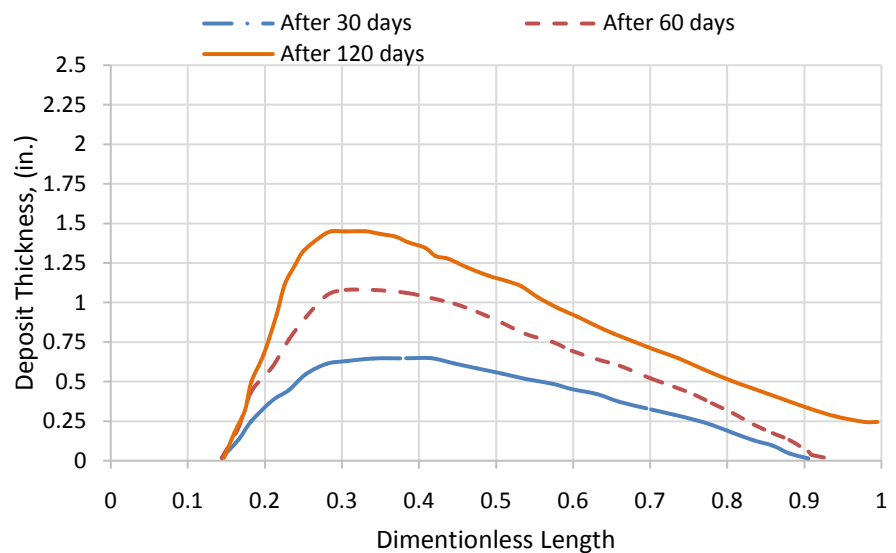**Figure 9.** Deposition thickness after 120 days.

Figure 10. Comparison of deposition thickness at different times.

4. Summary and Conclusions

The conclusions of the study can be described as follows:

- Asphaltene precipitation and deposition region in the production wells can be predicted by the proposed approach.
- Asphaltene deposits thickness in precipitation region is calculated at different time intervals, *i.e.* 30, 60 and 120 days. After 120 days, deposited asphaltene thickness exceeds more than 50% of tubing radius; therefore, a reduction in flow rate, an increase in pressure drop and tubing blockage are expected.
- It is shown the deposits thickness along the wellbore has approximately a skew normal distribution shape, which could be the result of increases in velocity and excess pressure drop.

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