A Novel Method for Mitigation of Asphaltene Deposition in the Wellstring

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ABSTRACT: *Asphaltene precipitation and deposition is a serious problem in many Iranian fields. The deposited asphaltene results in partial or total blockage of the wellbore and wellstring reducing or completely seizing oil production. This paper studies the asphaltene problem and mitigation methods in wellstring systematically. It presents new approach based on the combination of thermodynamic modeling of asphaltene precipitation with hydrodynamic well modeling. The developed model is capable to determine the asphaltene precipitation and deposition interval through the wellstring. Therefore, it could study the effect of hydrodynamic parameters such as wellhead pressure, well flow-rate and tubing size on the mitigation of asphaltene deposition. The conventional way to treat asphaltene deposition was through remediation which attacks the problem after it occurs. This model is capable to determine the severity of asphaltene deposition even before start of production. The model was applied to simulate the asphaltene precipitation in one of the south Iranian oil fields (Kupal) and important guidelines have been studied to mitigate the risks associated with asphaltene deposition. The results of modeling show that change in hydrodynamic condition could reduce and mitigate asphaltene deposition damage. But in some cases it would not be possible to prevent asphaltene precipitation completely. Therefore, the approach for flow assurance in those cases would be to change the well completion and inject asphaltene inhibitor, in order to prevent deposition of asphaltene flocculates.*

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INTRODUCTION

Petroleum asphaltenes are defined as soluble class of the heavy components in crude oil in a non-polar solvent such as pantene [1]. Asphaltenes are poly-aromatic structures or molecules, containing heteroatom (i.e. S, O, N) and metals (e.g. Va, Ni) that exist in petroleum fluids in an aggregated state [2]. These aggregates are stabilized in solution by resins and aromatics, which act as peptize agents [3]. Asphaltenes and resins, are in the thermodynamic equilibrium at static reservoir condition. However, changes in thermodynamic condition such as pressure, temperature or compositions during oil production may cause stabilized asphaltenes precipitate out of fluid and could deposit in reservoir, wellbore, wellstring, transport pipeline or surface processing facilities [4].

Since pressure and temperature change extremely through production string, it is the most susceptible area for asphaltene precipitation.

Deposition of asphaltene on the wall of production string reduces available diameter to oil flow, subsequently, oil production rate decreases. Gradually, oil flow path is plugged by increasing the thickness of deposited asphaltene. In addition to economical damages as a result of seizing oil production, the cost of removing asphaltene obstruction plug by chemical or mechanical treatment can increase.

The conventional way to treat asphaltene deposition was through remediation that includes solvent soaks with aromatic solvent and/or aromatic solvent blended with dispersants and physical removal such as wirelining, hydroblasting and drilling. These treatment methods attack the problem after it occurs [5].

It is essential to determine the depth of asphaltene deposition in order to implement proper method for mitigating or preventing the asphaltene deposition damages. *Haskett et al.* [6] are the first who studied asphaltene deposition in well string of Hassi Messaoud field. They expressed that asphaltene dose not occur after the pressure falls below bubble point. *Thawer et al.* [7] and *Alkafeef et al.* [8] stated asphaltenes start to deposit within the windows of asphaltene flocculation onset pressure to the bubble point pressure. Recently, the authors of this paper showed that, asphaltenes precipitate in window that is limited by asphaltene flocculation onset

pressure and cross point of hydrodynamic and thermodynamic condition [9].

In this paper, a comprehensive method is presented for prediction of asphaltene precipitation in wellstring. The method is based on the combination of thermodynamic and hydrodynamic modeling through well column.

A new simplified thermodynamic model was developed base on the scale equation for modeling of asphaltene precipitation from live oil. The developed thermodynamic model has been applied to describe the asphaltene precipitation due to pressure and temperature changes during lifting up of reservoir fluid to the wellhead. The hydrodynamics modeling assists the *Begges & Brill* correlation [10] for calculating the pressure and temperature profiles along the well column.

Finally, a series of modeling has been conducted in order to study the operational condition that includes the wellhead pressure, tubing size and oil flow rate on the asphaltene problem in well column of one of the Iranian south oil fields. The Results of modeling has been considered to mitigate asphaltene deposition. This study provides a number of results of practical importance for asphaltene precipitation and modeling in the wellstring.

PROBLEM STATEMENT

Numerous problems encountered in oil production have been associated with asphaltene deposition in the wellstring of some oil fields. Deposited asphaltene could be removed from wellstring by chemical/mechanical treatments. Nevertheless in most cases, plugging occurs again after a short time.

Asphaltene through the wellstring may deposit on the wall of tubing and downhole equipments. Deposition of asphaltene on the downhole equipment may disable them from normal functionality. Asphaltene deposition in tubing causes multifarious problems for wireline operations, because, the wireline tools may stick in the tubing. Therefore, some of the tests will not be carried out. Consequently lack of reservoir information could cause mismanagement on the reservoir performance.

Most of Bangestan oil fields in south of Iran have a serious problem with asphaltene deposition in wellstring. This problem has been observed periodically and has caused various operational problems in some wells.

This study tries to find an approach which could mitigate asphaltene deposition in wellstring to reduce the operational production cost.

ASPHALTENE THERMODYNAMIC MODELING

Several different thermodynamic models have been introduced for modeling of asphaltene precipitation from live oil. First model is based on real solution which presumes asphaltene is dissolved completely in oil [11-14]. In this model, precipitation of asphaltene as solid phase is described by reducing its solubility in the oil phase. The asphaltene precipitation is assumed a reversible process.

The second model is the colloidal model which considers the asphaltene molecules dispersed and suspended colloidally in the oil that peptized by resins [15,16]. Based on this model asphaltene molecules flocculate if resins concentrations are diluted. Colloidal model considers asphaltene precipitation an irreversible process.

The scale equation is another method for modeling asphaltene precipitation Therefore, a simple new scale model has been developed for modeling of asphaltene precipitation from live oil in different pressure and temperature conditions.

The first scale model was presented by *Rasamdana et al,* [17]. They have shown that all titration curves of asphaltenic dead oil with normal alkane solvents will collapse into a single curve. All variables involved in asphaltene precipitation were combined in the two variables which are as follows:

$$X = \frac{R}{M^z} \qquad \text{and} \qquad Y = \frac{W}{R^{z'}} \qquad (1)$$

z and z' are two adjustable parameters which must be carefully tuned to obtain the best fit of the experimental data. They suggested z' = -2 as a universal constant regardless of oil and precipitant used and z = 0.25.

Hu et al [18] evaluated the universality of exponents z and z' and concluded that z depends on oil composition varying from 0.2 to 0.5 but z' is effectively universal. In recent years, the validity of scaling model is verified by several investigators [19-20] (i.e. for titration of dead oils with normal alkane solvents under isothermal condition).

Rassamdana et al. [21] extended the scaling model to non-isothermal asphaltene precipitation process by including the temperature in the scaling variables X and Y as follow:

$$X = \frac{R}{M^z T^{c_1}} \qquad \text{and} \qquad Y = \frac{W}{R^{z'} T^{c_2}} \qquad (2)$$

They reported that the non-isothermal data can be correlated well by setting the exponent C1 and C2 equal to 0.25 and 1.6, respectively. Recently, *Hu & Guo* [22] performed extensive titration experiments on dead oil at several temperatures and concluded that the scaling Eq. (2) are adequate for correlating and predicting the asphaltene precipitation data at different temperatures for normal alkane precipitants but with exponent z, C1 and C2 equal to 0.25, 0.5 and 1.6, respectively.

The same analogy has been used to develop new scale equation for the live oil. Increasing the normal alkane concentration is the main factor of asphaltene precipitation form the dead oil, but for the live oil in the isothermal condition, change in the pressure is the major factor that causes the asphaltene precipitation.

Furthermore, after the onset point, amount of asphaltene precipitation increases with increase of concentration of normal alkane in the original scale equation, while laboratory tests demonstrate that after onset point and before bubble point pressure, amount of asphaltene precipitation increases with pressure increase and reaches to maximum at the bubble point. Asphaltene precipitation decreases with pressure increase when pressure is above bubble point.

Therefore, two distinct scale equations should be developed for the both upper and lower bubble point pressures.

To extend the original scaling model to live oil for the entire range of pressures and for non-isothermal condition, following extensive mathematics, the best fit of the experimental data is obtained by combining operating pressure, upper and lower onset pressures and temperature of live oil into the following two new dimensionless scaling variables X and Y:

$$X = \frac{p - p_{onset}}{p_b (T/T_c)^z} \qquad \text{and} \qquad Y = \frac{W}{W_c \left[(p - p_{onset})/p_b \right]^{z'}} \qquad (3)$$

Two scale equations for the upper and lower bubble point pressure has been proposed by tuning the z and z'. The result of live oil scale equation for higher than the bubble point pressure is illustrated in Fig. 1 (with Kupal data and two sets of data in the literature [23,24] where

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Table 1: Scale Equation parameters.

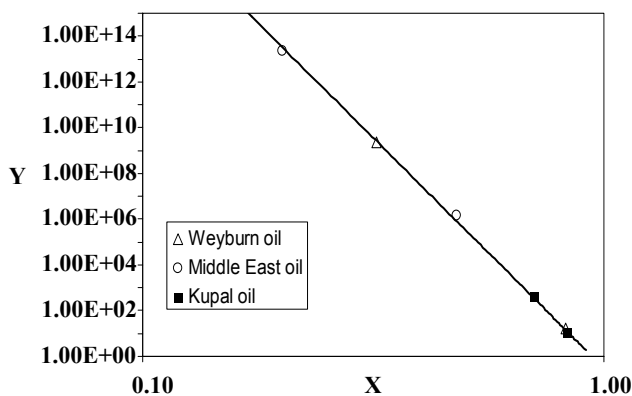| Parameter	z	z'	m	n
Upper bubble point	0.3851	20.335	-0.52746	-20.822
Lower bubble point	0.3647	20.335	-1.16893	-20.124

Fig. 1: Result of developed scale equation for live oil.

the plot of dimensionless Y against dimensionless X resulted in a single curve with the following general expression for upper and lower asphaltene deposition envelope:

$$\ln Y = m + n\ln X \qquad (4)$$

The values of constants z, z', m and n for upper and lower asphaltene deposition phase envelopes are given in Table 1.

As could be seen from table 1 the z' is same for the upper and lower bubble point scale equation. It supports the idea of universal like the scale equation for the dead oil.

HYDRODYNAMIC WELL MODELING

Reservoir fluids lose their energy by decreasing temperature and pressure during lifting up in well column. Hydrodynamic of fluid flow in the well column could be described by energy equation which is an expression for the balance or conservation of energy between bottomhole to the surface of the well. The energy equation can be written as:

Δ{[Internal Energy]+[Energy of expansion or contraction]+[Kinetic Energy]+[Potential Energy]+[Heat added to system]+[Work done by system]}=0

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i.e.

$$U_1 + P_1V_1 + \frac{mv_1}{2g} + \frac{mg.h_1}{g_c} + Q - W_s = \qquad (5)$$

$$U_2 + P_2V_2 + \frac{mv_2}{2g} + \frac{mgh_2}{g_c}$$

In different form per unit mass:

$$dU_1 + \frac{vdv}{g_c} + \frac{dp}{\rho} + \frac{g}{g_c}.dh + dQ + dW = 0 \qquad (6)$$

From thermodynamics, we can define the internal energy term as:

$$dU = dH - d\left[\frac{p}{\rho}\right] \qquad (7)$$

Where system entropy is:

$$dH = TdS + \frac{dp}{\rho} \qquad (8)$$

Substituting for the internal energy in Eq. (6) gives:

$$T.dS + \frac{dp}{\rho} + \frac{vdv}{g_c} + \frac{g}{g_c}.dh + dQ + dW = 0 \qquad (9)$$

However, for an irreversible process, we can apply the Clausius inequality:

$$dS \geq \frac{dQ}{T} \qquad (10)$$

Or

$$T.ds = dQ + dE_w \qquad (11)$$

Where dEw = energy losses due to irreversibilities. Assuming Equation 10 is valid and that dW = 0, we can obtain the general equation:

$$\frac{dp}{\rho} + \frac{vdv}{g_c} + \frac{g}{g_c}.dh + dE_w = 0 \qquad (12)$$

$$\frac{dp}{dh} = \frac{g}{g_c}\rho_s \sin\alpha + \frac{f\rho_f v_m^2}{2g_c d} + \frac{\rho v_m dv_m}{g_c dh} \qquad (13)$$

The pressure drop is attributable to three sources of friction, hydrostatic and kinetic energy losses. The first term represents the hydrostatic pressure gradient that depends on the density of fluid and the second term represents friction pressure loss due to the share stress at the pipe wall and the last term is kinetic energy.

Many correlations have been developed for predicting hydrodynamic modeling of well which differ in the manner used to calculate these three components of the total pressure gradient. *Begess & Brill* developed a method which divides the flow conditions into different regimes and assists different correlation for each flow regime.

This correlation is well accepted in petroleum engineering because of the applicability in modeling of flow in wide range of flow variables. It was the reason that this correlation has been chosen for hydrodynamic modeling in this paper.

The equations of pressure drop calculation are described elsewhere [25] therefore they will not be discussed here.

However, as soon as well starts to produce fluids from a reservoir, well temperature continuously changes until a steady-state condition is reached. This is because hot fluid flowing to the well bottom and rising in the well progressively heats up the well's surroundings.

Prediction of fluid temperature in the wellbore as function of depth and time is necessary to determine fluid physical properties required for calculating pressure gradient. On the other hands, accurate prediction of well temperature is an important task in thermodynamic modeling of asphaltene precipitation. Prediction of temperature in the wells requires application of conservation of mass, momentum and energy principles. This can be accomplished by coupling the pressure gradient and enthalpy gradient equation.

Sager et al. [26] built a comprehensive mathematical model for description of temperature condition in wells producing multiphase mixture. They assumed steady-state condition and included the effect of all the possible sources having impact on the well temperature such as heat transfer in the well completion and formation, changes in kinetic and potential energy, and the Joule-Thomson effect. Their final differential equation, therefore, is a strong formation for accurate temperature calculation.

In order to develop a calculation model suitable for potential application, the authors proposed a simplified solution and presented a correlation based on measured temperature profile.

Sager et al correlation for calculation of flowing temperature of the multiphase mixture at a vertical distance of z, measured from the well bottom:

$$T_f(z) = T_r(z) - \frac{A\sin\alpha}{Jc_l} + AF_C + Ag_g\sin\alpha + Exp(-\frac{z-z_o}{A})[T_f(z_o) -$$

$$T_r(z_o) + \frac{A\sin\alpha}{Jc_l} - AF_c - Ag_g\sin\alpha] \tag{14}$$

Where the factor A is called the relaxation distance and is calculated as:

$$A = \frac{6wc_l}{\pi r_{ti}U}[k_r + \frac{r_{ti}Uf(t)}{12}] \tag{15}$$

Mass flow rate w, and specific heat c_l of the flowing fluid is calculated from the formulas as follows:

$$w = \frac{1}{86400}[350(q_o\gamma_o + q_w\gamma_w) + .0764q_g\gamma_g] \tag{16}$$

$$c_l = c_o\frac{1}{1+WOR} + c_w\frac{WOR}{1+WOR} \tag{17}$$

Rock temperature at the known and the required vertical distance z_o and z, respectively, are found from the bottomhole temperature and geothermal gradient:

$$T_r(z_o) = T_{bb} - g_g z_o \sin\alpha \tag{18}$$

$$T_r(z) = T_{bb} - g_g z \sin\alpha \tag{19}$$

Correction factor F_c represents the sum of kinetic and Joule-Thomson effects. This factor is negligible when mass flow rate is greater than 5 lb/sec, and for lower, mass flow rates the following correlation is proposed:

$$F_c = 02.987E - 3 + 1.006E - 9p_{wb} + 1.906E - \tag{20}$$
$$4w - 1.047E - 6GLR + 3.229E - 5API + 4.009E - 3_g - 0.3551g_g$$

Sagar et al. derived the following formula valid for the usual wellbore sizes and for the time exceeding one week:

$$F(t) = 3.53 - 0.272r_b \tag{21}$$

Asphaltene deposition on the production conduit affects the overall heat transfer coefficient. This term is calculated as follow:

$$U_{Total} = \tag{22}$$
$$\frac{1}{R_{fluids} + R_{Analous} + R_{Tubing} + R_{Casing} + R_{Cemet} + R_{ground}}$$

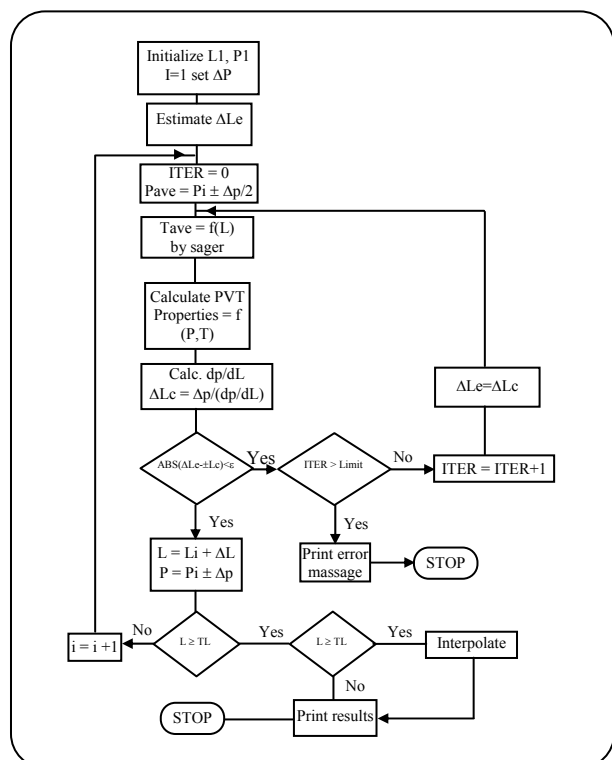In general, the overall heat transfer coefficient is the reciprocal of the sums of the individual resistance to

Components	H$_2$S	N$_2$	CO$_2$	C$_1$	C$_2$	C$_3$	IC$_4$	NC$_4$	IC$_5$	NC$_5$	FC$_6$	FC$_7$	FC$_8$	FC$_9$	FC$_{10}$	FC$_{11}$	C^{12}
Mole (%)	1.87	0.31	3.37	43.60	8.58	6.27	1.64	4.89	2.20	2.49	1.91	0.89	3.01	2.05	1.84	1.39	13.7
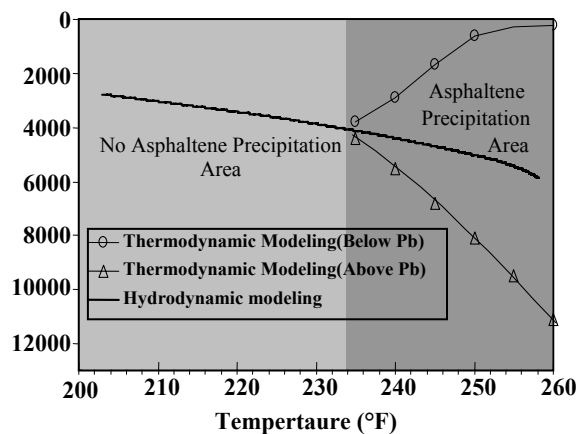
Fig 3: asphaltene precipitation envelope in wellstring.

Fig. 4: Matching scale equation model with Experimental data at 250 °F.

The asphaltene precipitation well modeling was carried out with Matlab programming software.

Modeling of asphaltene precipitation in the wellstring studied and different ways was investigated to mitigate the problem. The results of modeling in kupal filed are as follows:

Thermodynamics modeling

For thermodynamic modeling of asphaltene precipitation, bottom-hole sample should be taken to be as representative reservoir fluid. Because some of the asphaltene may deposit in tubing, therefore surface sampling may give an error. In order to avoid any inaccuracy, bottom-hole reservoir fluid sample was taken form the Kupal reservoir.

Routine PVT experiment such as flash, differential, separator test and reservoir fluid composition were carried out. Kupal reservoir oil composition is given in Table 2. Asphaltene precipitation measurements with filtration method were performed. The Asphaltene test was carried out according to the Standard IP143. Table 3 shows the result of SARA test.

In filtration experiment, small amount of live oil is passed through a 0.5 micron hydrophobic filter at different pressures. Temperature in all the experiment was set at 250 °F. The precipitated asphaltene on the filter were measured in weight percent of original sample.
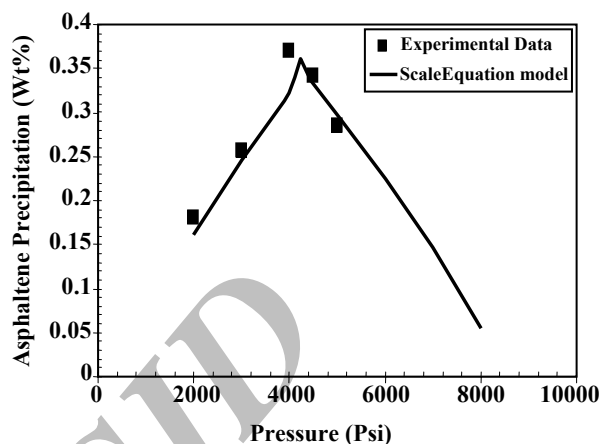
The developed scale equation has been applied for modeling of asphaltene precipitation for the kupal experiments. Table 4 presents the general data that has been used in the scale equation.

Fig. 4 shows the quality of the matching which is the reason for the ability of the solubility thermodynamic model in prediction of asphaltene precipitation.

Hydrodynamics modeling

Hydrodynamic modeling was carried out by using *Begges & Brill* correlation. First, the correlation should be tuned with field data, and then it could be used for modeling different hydrodynamic conditions. Therefore, the correlation was tuned with Production Logging Tools (PLT) data. In order to avoid sticking the PLT tools in the wellstring, test was run after washing the well column with xylene. Result of PLT test showed that the well flow rate and flowing bottom-hole pressure were 5893 STBD and 5540 psi, respectively.

Fig,. 5 shows the matching of hydrodynamic model with PLT field test.

Asphaltene precipitation in the wellstring was modeled with coupling the hydrodynamic and thermodynamic models. Fig. 6 shows the result of asphaltene precipitation modeling for one of the kupal wells.

As Fig. 6 shows the asphaltene precipitation starts from the wellbore and continues to the depth around 7200 ft.

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Table 3: Results of SARA analyses of kupal.

Fraction	Saturated	Aromatic	Resin	Asphaltene
Wt (%)	52.49	41.04	5.48	0.99

Table 4: General reservoir fluid data..

Reservoir Temperature(F)	250
Saturation pressure(Psi)	3950
Upper onset pressure at reservoir temperature	8100
Lower onset pressure at reservoir temperature(psi)	600
Critical Temperature(K)	964.7
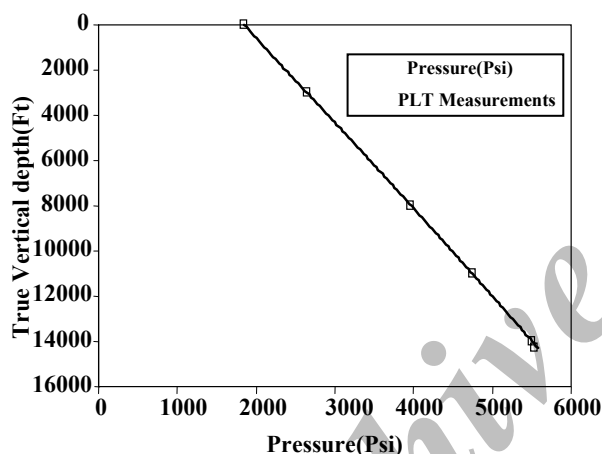
Fig. 5: hydrodynamic model matching with PLT.
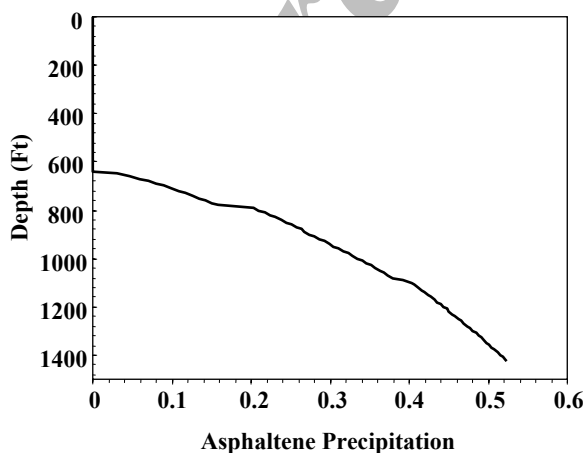
Fig. 6: Modeling of Asphaltene Precipitation amount and profile.

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At shallower depths asphaltene does not precipitate. As oil expands up from wellbore to the wellhead, it experiences decline in pressure and temperature. Hence, thermodynamics well flowing conditions get in region out of asphaltene deposition envelope. As result, fluid flow could be assured by preventing asphaltene precipitation in the interval that is in the region of the asphaltene deposition envelope.

Different method of mitigation of asphaltene deposition problem has been studied for Kupal that are as follows:

Change in hydrodynamic conditons

Hydrodynamic condition has direct impact on the profile of pressure and temperature, consequently, changes the behavior of asphaltene precipitation in the wellstring. Hence, effect of different controllable hydrodynamic parameters has been considered on the mitigation of asphaltene precipitation problem. These parameters are wellhead pressure, oil flow rate and the tubing diameter size.

Authors described the effect of hydrodynamic parameters in detail. The results of modeling are:

• Change in wellhead pressure: One of the controllable hydrodynamics parameter for mitigation of asphaltene precipitation is wellhead pressure which is dependent on the back-pressure of separator and the path from wellhead to the process unit. The minimum wellhead pressure required for oil flow to production unit is 500 psi. Fig. 7 shows the result of asphaltene precipitation modeling for the well-head pressures of 500,1650,1900,2350 and 2600 psi. The result of hydrodynamic modeling shows that decreasing the wellhead pressure reduces both the amount and interval of asphaltene precipitation.

• Change of well flow rate: In order to study the effect of oil flow rate on the asphaltene problem in well column, sensitivity was carried out in range of minimum economic oil flow-rate and the maximum ability of reservoir flow with current completion which is 1000 and 10000 STBD, respectively. As has been shown in Fig. 8 the hydrodynamic modeling indicates asphaltene precipitation interval increases with increasing oil flow rate.

• Change of tubing diameter size: According to Fig. 9, the molding shows that asphaltene precipitation reduces with increasing the tubing size. Considering the
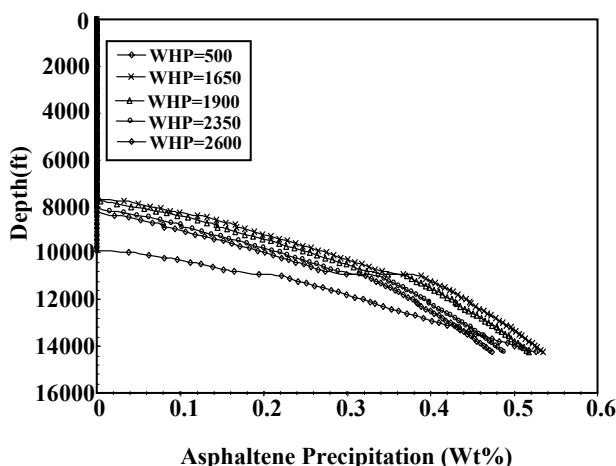
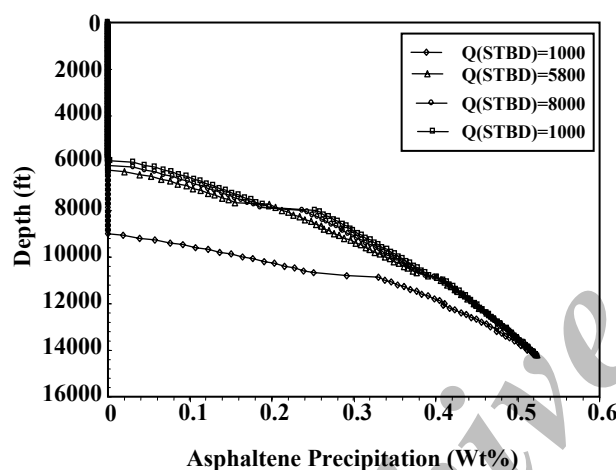**Fig. 7: Effect of WHP on the asphaltene precipitation.**

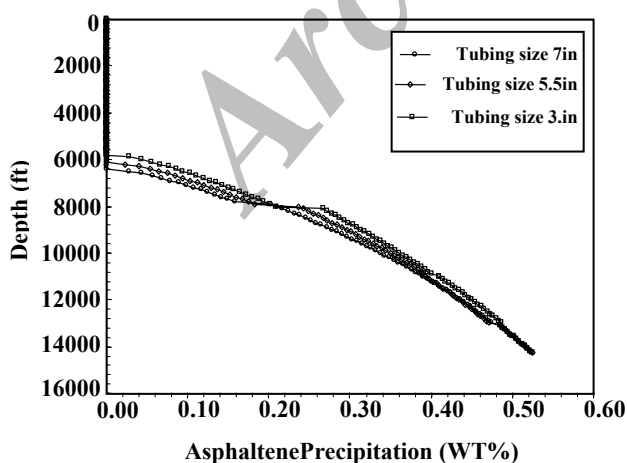**Fig. 8: effect of flow rate on the asphaltene precipitation.**

Fig. 9: effect of tubing size on the asphaltene precipitation.

result of hydrodynamic modeling, although they could mitigate the asphaltene precipitation problem but they cannot prevent asphaltene precipitation completely.

Change in well completion

As it was mentioned, producing fluid is in thermodynamic condition that even change of hydrodynamic parameters could not prevent the asphaltene precipitation because profile of pressure and temperature of well passes through asphaltene deposition envelop. In other words, the asphaltenes come out of solution and several particles may combine to form precipitate. When the particles become sufficiently large and heavy they tend to deposit [27]. Therefore, our suggested method to prevent the asphaltene deposition is to change completion and injection of the inhibitors from the bottomhole. These asphaltene inhibitors have stronger association with asphaltene and are able to stabilize the asphaltene through changes in pressure and temperature.

However, the Inhibitors will disperse precipitated asphaltenes and prevent deposits in the wellstring.

Fig. 10 shows the schematic of well at present and the proposed one for remedial of asphaltene deposition in wellstring.

CONCLUSIONS

Asphaltene precipitation and deposition has been studied systematically with considering the thermodynamic and hydrodynamic model in details for the Kupal field. Simple applicable scale model has been developed for thermodynamic modeling of asphaltene precipitation.

The new approach has been presented for determination of asphaltene precipitation and deposition problem along the wellstring that could be applied in each field. This approach has been applied to investigate the possibility of operational condition such as wellhead pressure, oil flow rate and tuning size in order to prevent and/or mitigate in the kupal oil field.

Results of modeling show that by reducing wellhead pressure and oil flow rate and increasing the tubing size the asphaltene precipitation decreases. Although changes in operational condition improve the asphaltene precipitation in this field but could not resolve the problem completely. Therefore, another approach for flow assurance based on change in completion and continues injection of asphaltene inhibitor was presented.
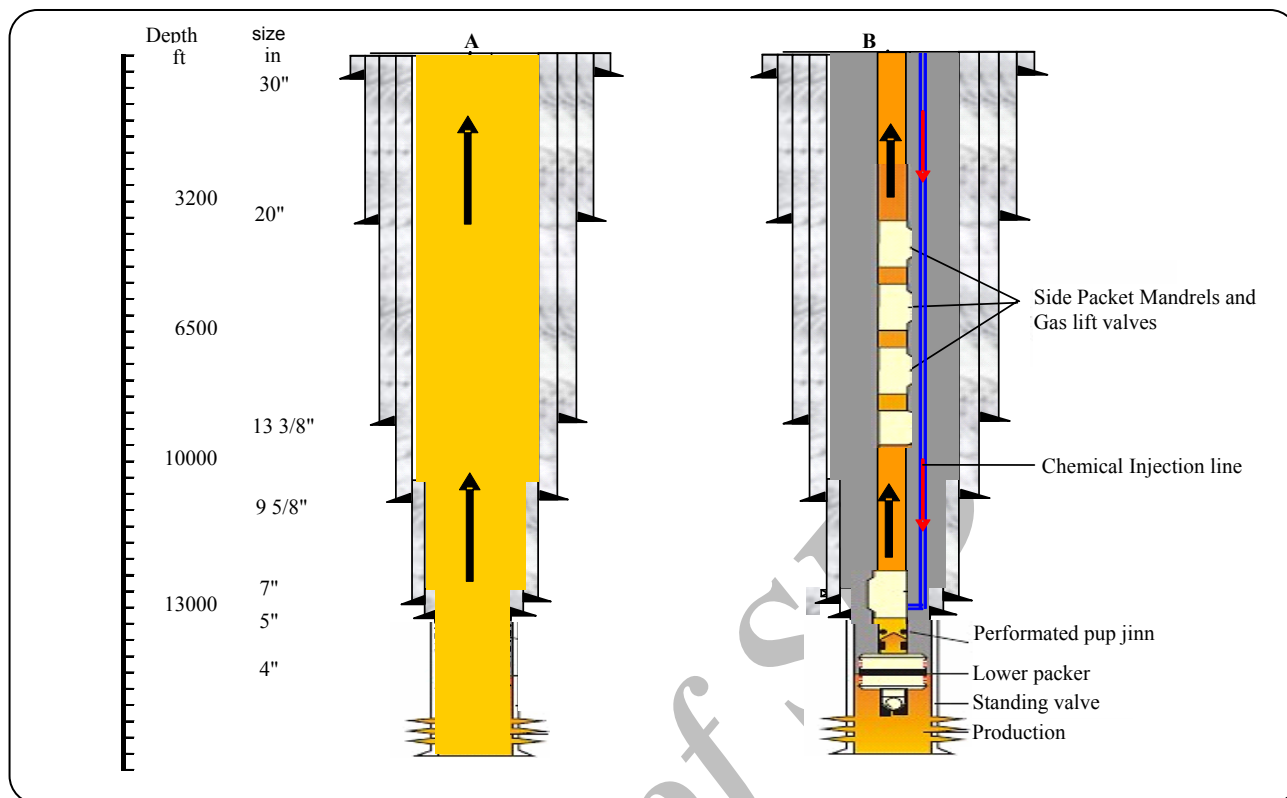
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Fig. 10: Current and proposed well completion.

Nomenclatures

A	Relaxation distance, (ft)
c	Specific heat, (Btu/lb/°F)
E_w	Energy losses due to irreversibility, (kJ)
F_c	Correction factor, (dimentionless)
GLR	Producing gas-liquid ratio, (scf/stb)
g_g	Geothermal gradient, (°F/ft)
H	System enthalpy
h	Depth, (ft)
k_r	Thermal conductivity of rock material, (Btu/d/ft/°F)
Q	Heat added or removed (kJ)
P	Pressure, (psi)
R	Solvent to oil ratio, (cc/g)
r_h	Wellbore inside radius, (in)
S	Entropy
T	Temperature, (°F)
T_r	Rock temperature, (°F)
T_f	Folwing fluid temperture at z_o , (°F)
T_{bb}	Bottom hole temperture , (°F)
U	Internal Energy (kJ/mol)

$U_{vaporzation}$	Internal energy change during the vaporization of a unit mole of oil, (kJ/mol)
U	Overall heat transfer coefficient, (Btu/day/ft^2/°F)
v	Fluid velocity , (m/s)
V_A	Molar volume of asphaltene, (L/mol)
V_L	Molar volume of oil phase, (L/mol)
W	Weight percent of asphaltene precipitation
W	Work done or supplied
w	Mass flow rate, (lb/day)
X	Scaling parameter
Y	Scaling parameter
z	Vertical distance, measured from the well bottom, (ft)
z_o	Vertical distance, where temperature are known, (ft)

Greek

α	Deviation angle, degree
ρ_L	Density of oil phase, lb/ft^3
ρ_A	Density of asphaltene, lb/ft^3
γ	Specific gravity ,dimensionless

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Subscripts

A	Asphaltene
g	Gas
L	Liquid
O	Oil
w	Water
z	Constant in scale equation
z'	Constant in scale equation
C1	Constant in scale equation
C2	Constant in scale equation

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