SIMULATION OF PARAFFIN DEPOSITION IN PETROLEUM RESERVOIRS

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ABSTRACT

Paraffin deposition within petroleum reservoir during crude oil production can cause a decrease in reservoir performance, consequently the need to predict wax deposition is a major concern to all petroleum producers. The paper presents the development processes of a numerical simulator to model the deposition of Paraffin in the reservoir and it also shows the effects of the Paraffin (wax) deposition on the skin factor in the reservoir. A one-dimensional, three-phase and four-pseudo-component model for paraffin deposition was developed. The paraffin retention by static and dynamic pore surface depositions and pore throat plugging were considered. A fully implicit finite difference numerical scheme was developed and solved by a double iteration procedure. The model when applied to a typical field condition showed that the wax precipitation and consequently deposition to be a near well-bore phenomenon where the pressure gradient is relatively higher than those attainable far in the reservoir. Though little, the paraffin deposition was shown to cause decrease in the porosity, permeability and consequently higher skin in the porous medium especially near the well-bore region. Hence frequent stimulation by heat treatments of the near well-bore region is highly advisable for wells which produce high waxy crude so as to neutralize the skin effects cause by wax deposition in the region.

Keywords: Paraffin deposition, pore throat plugging, heat treatment, skin effect, productivity index.

NOMENCLATURE

 $a_{GL} = \mbox{mass}$ fraction of the dissolved gas in the liquid phase, dimensionless

 a_{OL} = mass fraction of the oil component in the liquid phase, dimensionless

A = Cross sectional area

 C_L = Saturation of liquid phase, dimensionless

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 C_S = Saturation of paraffin (solid) phase, dimensionless

 C_G = Saturation of gas phase, dimensionless

D = Diffusion coefficient

 ΔV = change in molar volume

h = Height

 H_F = enthalpy of formation, cal/cm³

 H_L = enthalpy of liquid phase, cal/cm³

 $H_{\rm S}$ = enthalpy of paraffin (solid) phase, cal/cm³

 H_G = enthalpy of gas phase, cal/cm³

k = current permeability, darcy

k_{i =} initial permeability, darcy

 $K_{sp} =$ Solubility product

K_L = thermal conductivity of liquid, cal/sec-cm-K

 K_S = thermal conductivity of paraffin, cal/sec-cm-K

 K_G = thermal conductivity of gas, cal/sec-cm-K

 K_F = thermal conductivity of formation, cal/sec-cm-K

 k_{G} = relative permeability of the gas phase, dimensionless

 k_1 = relative permeability of the liquid phase, dimensionless

 M_g , M_o , M_s = Molecular weight of gas, oil and paraffin respectively g/g-mole

P = pressure

q = flow rate

r = radial distance

 $_{\rm S} = {\rm paraffin}$

S = Skin factor

T = Temperature

 T_{sm} = melting point temperature of paraffin, ^oC

 v_{lr} = radial velocity of the liquid phase, cm/s

 v_{vr} = radial velocity of the vapour phase, cm/s

 X_{sl} = mole fraction of paraffin dissolved in the liquid, dimensionless.

Symbols

 μ_l = viscosity of the liquid phase, cp

 μ_g = viscosity of the gas phase, cp

 ϕ = porosity

 γ_i = activity coefficient

 σ = volume fraction of deposited paraffin fraction

 ρ_F = density of formation, g/cm³

 ρ_s = density of paraffin, g/cm³

 ρ_l = density of liquid phase, g/cm³

 ρ_{g} = density of gas phase, g/cm³

Subscripts

F formation g gas o oil s solid (wax) sc standard condition i initial l liquid

INTRODUCTION

With the increasing demand of crude oil all over the world and also as the search of crude oil moves into deep offshore, the focal point of oil and gas exploration and production has advanced to the deep offshore where drilling operation have been accomplished in great depth of water. Production from deep offshore reservoirs have been met with a lot of constraints ranging from the implementation of cutting edge and very expensive technology, intelligent completion, also the problem of transporting the produced reservoir fluid to production platform and subsequently to export terminal.

The occurrence of wax deposition in oil reservoirs has proven to be a headache to reservoir engineers especially in deep offshore operations. Wax is a hydrocarbon component consisting mainly of normal alkanes, varying amounts of condensed cycloalkanes, isoalkanes and occasionally a very high percentage of aromatic material. Molecular weight of paraffin wax is usually less than 450, and the viscosity at 210°F normally would be less than 6 centistokes. Most paraffin solids are mixtures of hydrocarbon ranging from C_{19} to

C701.

In the reservoir, the precipitated paraffin particles are within the pores of the reservoir. This further leads to the permeability of the reservoir in the region of the deposition to decrease. The effect of this eventually results in a decrease in reservoir flow rate, mostly near the wellbore to occur. Low temperatures reservoirs are liable to suffer paraffin precipitation and permeability damage especially when crude oil is cooled below cloud point (precipitation point). Formation permeability dictates the extent of damage, amount of precipitated paraffin and the bottom hole temperature.

Paraffin deposition in reservoirs consists of three mechanisms which include:

(1)		S
	olubility/precipitation of paraffin,	
(2)		D
	eposition of precipitated paraffin, and	
(3)		R
	eduction in porosity and permeability caused by paraffin deposition.	

The solubility/precipitation of paraffin has been studied by many authors (Ring, 1991, Erickson *et al.*, 1993, Brown *et al.*, 1994, Lira-Galeana *et al.*, 1996, Hammani and Raines, 1999, Coutinho *et. al.* 2001). Different models had been suggested to model the deposition of

paraffin in reservoirs, these include thermodynamic models, empirical models, trajectory analysis models, stochastic models and network models to mentioned but a few. The inadequacies in most of these models lie in their assumptions of the fluid's and rock's properties which are not representative of the real conditions operating in petroleum reservoirs.

MODEL DEVELOPMENT

A mathematical model is developed for flow of solid paraffin in a porous media. The following assumptions are made: (1) the flow is in radial direction. (2) The gravity effects are neglected; (3) the capillary pressure effects between vapour and liquid phases can be neglected; (4) the oil, gas, and solid (paraffin) phase are at the same temperature for a space point.

Continuity Equation

The mass balance equations are expressed separately for the oil, gas and paraffin (solid) pseudo-components, denoted respectively by O, G, and S. the vapour and the liquid phase are denoted by V and L

The continuity equation for flow of gas through porous media for a gas-liquid system is expressed as

$$\frac{\partial}{\partial t} \left(\phi C_{g} \rho_{g} + \phi C_{L} \rho_{l} a_{GL} \right) = -\nabla \left(\rho_{g} v_{gr} + \rho_{L} v_{lr} a_{GL} \right)$$
⁽¹⁾

Since the gas component exists both in the gas and liquid phases, both the free gas and the dissolve gases are considered in the gas component continuity equation.

The oil component exist only in the liquid phase (dissolved gas already taken care of in the gas component above), hence the continuity equation is given by;

$$\frac{\partial}{\partial t} (\phi C_L \rho_l a_{OL}) = -\nabla (\rho_l v_{lr} a_{OL})$$
⁽²⁾

The continuity equation for flow of solids through porous media for a liquid-solid system is expressed as (Ring *et al.*, 1994)

$$\frac{\partial}{\partial t} (\phi \rho_s (1 - \sigma) C_s + \phi \rho_s \sigma) = -\nabla . (\rho_s C_s v_{lr})$$
⁽³⁾

The continuity equation, equ. (3), considers conservation of solid paraffin particles (mass) for any coordinate system, with no change in solubility/precipitation. The paraffin is divided between suspended and deposited solid particles. The mass of suspended paraffin/bulk

volume is represented by $\phi_s(1-\sigma)C_s$ the mass of deposited paraffin/bulk volume is represented by $\phi_s\sigma$. The flow rate of suspended paraffin/unit cross-sectional area is represented by, $\rho_s C_s v_b$. The deposited paraffin does not flow.

Assuming a constant paraffin density, the continuity equation above is reduced to:

$$\frac{\partial}{\partial t}(\phi(1-\sigma)C_s + \phi\sigma) = -\nabla (C_s v_{lr})$$
(4)

Rearranging,

$$\frac{\partial}{\partial t}(\phi(1-\sigma)C_s) = -\nabla .(C_s v_{lr}) - \frac{\partial}{\partial t}(\phi\sigma)$$
⁽⁵⁾

Paraffin Deposition Model

The continuity equation can be simplified by assuming a constant local radial velocity, v_{lr} and porosity ϕ , at the space point it then becomes:

$$\phi \frac{\partial}{\partial t} (1 - \sigma) C_s = -v_{lr} \nabla . C_s - \phi \frac{\partial \sigma}{\partial t}$$
⁽⁶⁾

$$\phi \left[(1 - \sigma) \frac{\partial C_s}{\partial t} + C_s \frac{\partial (1 - \sigma)}{\partial t} \right] + \phi \frac{\partial \sigma}{\partial t} = -v_{lr} \nabla C_s$$
(7)

Hence,

$$\frac{\phi(1-\sigma)}{v_{lr}}\frac{\partial C_s}{\partial t} + \frac{\phi(1-C_s)}{v_{lr}}\frac{\partial \sigma}{\partial t} = -v_{lr}\nabla C_s$$
(8)

Finally,

$$\frac{\phi(1-\sigma)}{v_{lr}}\frac{\partial C_s}{\partial t} + v_{lr}\frac{\partial C_s}{\partial r} = -\frac{\phi(1-C_s)}{v_{lr}}\frac{\partial \sigma}{\partial t}$$
(9)

From Fick's first law

$$J = -D\left(\frac{\partial C_s}{\partial r}\right) \tag{10}$$

And from Fick's second law,

$$\frac{\partial C_s}{\partial t} = -\frac{\partial J}{\partial r} \tag{11}$$

Hence,

$$\frac{\partial C_s}{\partial t} = \frac{\partial}{\partial r} \left(D \frac{\partial C_s}{\partial r} \right) \tag{12}$$

Assuming the diffusion coefficient is independent of position, i.e assuming a constant viscosity of the oil in the reservoir,

Generally the temperature difference between the WAT and the gel point will not exceed 30°C. It is known that the increase of (density of liquid (oil)/ density of solid (wax) at this temperature range will not exceed 2% (Peneloux et al., 1992), so the (density of liquid (oil)/ density of solid (wax) can be treated as a constant.

$$\frac{\partial C_s}{\partial t} = D \frac{\partial^2 C_s}{\partial r^2}$$
(13)

Substituting equ. (13) into equ. (9)

$$\frac{\phi(1-\sigma)}{v_{lr}}D\frac{\partial^2 C_s}{\partial r^2} + v_{lr}\frac{\partial C_s}{\partial r} = -\frac{\phi(1-C_s)}{v_{lr}}\frac{\partial \sigma}{\partial t}$$
(14)

Using Einsten's equation for particle diffusivity,

$$D = \frac{BT}{3\pi\mu \ d} \tag{15}$$

Substituting equ. (15) into equ. (14)

 $\partial \sigma$

$$\frac{\phi(1-\sigma)}{v_{lr}}\frac{BT}{3\pi\mu}\frac{\partial^2 C_s}{\partial r^2} + v_{lr}\frac{\partial C_s}{\partial r} = -\frac{\phi(1-C_s)}{v_{lr}}\frac{\partial \sigma}{\partial t}$$
(16)

And $\overline{\partial t}$ is the rate of paraffins deposition,

Simplifying Civan's model (1996), the rates of deposition of scale is given as (Wang *et al.*, 1999)

$$\frac{\partial \sigma}{\partial t} = \psi \ C_S \phi^{2/3} + \beta \ C_S \phi^{2/3} v_{lr} + \gamma \ C_S \phi \ v_{lr}$$
⁽¹⁷⁾

In equation (17), the first term represents the static surface deposition and ψ is the static surface deposition rate coefficient. The second term represents dynamic surface deposition and β is the dynamic surface deposition rate coefficient. The third term represents the pore-throat plugging deposition and γ is the plugging deposition rate coefficient.

The static surface deposition can occur even when there is no fluid flow. When fluid begins to flow, the dynamic surface deposition is predominant. Whether the plugging deposition will occur is determined by the following criteria:

$$\gamma = \gamma_i [1 + \eta \sigma] D_{pcr} < D_p$$
⁽¹⁸⁾

otherwise
$$\gamma \equiv 0$$
 (19)

 γ_i is the initial plugging deposition rate constant, D_p is the mean diameter of the particles. D_{pcr} is the critical mean diameter of the pore throats below which the pore throat plugging can occur and determined by the following formula:

$$D_{pcr} = D_{pt} A \left[1 - \exp\left(-\frac{BC_S v_{lr}}{\phi}\right) \right]$$
(20)

When D_p is larger than D_{pcr} , the pore throat plugging will occur.

The Darcy equation is used to describe the momentum balance for the liquid phase.

$$v_{lr} = \frac{kk_l}{\mu_l} \frac{\partial P}{\partial r}$$
(21)

and for gasphase

$$v_{gr} = \frac{kk_g}{\mu_g} \frac{\partial P}{\partial r}$$
(22)

The sum of the saturation of the gas and liquid phases and the paraffin suspended in the liquid phase is equal to 1.

$$C_G + C_L + C_S = 1$$

Assuming local thermal equilibrium, the total energy balance equation of the oil, gas, formation and solid system is set up as the following

(23)

$$\frac{\partial}{\partial t} \left[\phi C_{g} \rho_{g} H_{g} + \phi C_{v} \rho_{l} H_{L} + (\phi C_{s} + \sigma) \rho_{s} H_{s} + (1 - \phi - \sigma) \rho_{F} H_{F} \right] + \frac{\partial}{\partial r} (\rho_{v} v_{vr} H_{v} + \rho_{l} v_{hr} H_{L}) =
\frac{\partial}{\partial r} \left\{ \left[\phi C_{g} K_{g} + \phi C_{L} K_{L} + (\phi C_{s} + \sigma) K_{s} + (1 - \phi - \sigma) K_{F} \right] \frac{\partial T}{\partial r} \right\}$$

$$(24)$$

$$\frac{\partial}{\partial t} \left[\phi C_{g} \rho_{g} H_{g} + \phi C_{v} \rho_{l} H_{L} + (\phi C_{s} + \sigma) \rho_{s} H_{s} + (1 - \phi - \sigma) \rho_{F} H_{F} \right] + \frac{\partial}{\partial r} \left\{ (\rho_{v} v_{vr} H_{v} + \rho_{l} v_{hr} H_{L} - \phi C_{g} K_{g}) - \phi C_{L} K_{L} - (\phi C_{s} + \sigma) K_{s} \right\} = \frac{\partial^{2} T}{\partial r^{2}} (1 - \phi - \sigma) K_{F}$$

$$(25)$$

The time and space derivatives were discretized using the second order backward and central finite difference approximation respectively with equal time step and grid sizes. Since the equations are strongly coupled and non linear they are solved by double iteration method.

The temperature profile is the computed after each time step taken to determine the pressure, precipitation, depositional rate and the new porosity in the reservoir.

The paraffin solubility and precipitation are represented with ideal-solution theory (Oyekunle and Adeyanju, 2011) supported by the results generated and validated with experimental results given at elevated pressure, P as:

$$X_{Sl} = \exp\left[-\frac{\Delta H_{S}}{R}\left(\frac{1}{T} - \frac{1}{T_{Sm}}\right)\right] + \frac{\Delta V}{RT}\left(P - P_{SC}\right)$$
(26)

Figure 1 shows the validation of ideal solution theory with experimental results, the new porosity given by,

$$\phi = \phi_i (1 - \sigma) \tag{27}$$

Applications

The numerical solution of the equations developed in the preceding section is accomplished by mean of the implicit finite-difference method. The time and space derivatives are discretized using second order backward and central finite difference approximations respectively with equal time steps and grid sizes. A point centered grid system is used. Because the equations are strongly coupled and nonlinear, they are solved by double iteration method. The inside iteration solve for the pressure, temperature, and the velocity distributions with parameters and coefficients from last outside iteration. Then, the outside iteration solved for all the variables (pressure, Temperature, saturation and deposition) together with renewal of the values of the parameters and coefficients.

The permeability reduction was computed using Civan et al. (1989) power law:

$$\frac{k}{k_i} = \left(\frac{\phi}{\phi_i}\right)^m \tag{28}$$

This equals,

$$\frac{k}{k_i} = (1 - \sigma)^m \tag{29}$$

The phenomenological constant, m, was determined empirically by matching simulated results with the experimental results with the experimental results of Sutton and Roberts (1974). Although Civan (1995) recommended a value of 3.0, a better match of the experimental results was obtained with m = 8.0 according to Ring et al. (1994).

SKIN FACTOR AND PRESSURE LOSS

The skin factor, S, is a dimensionless number representing the degree of formation damage caused by the positive pressure differential between the wellbore and formation by depositions such as paraffin wax around the well bore. S is calculated by

$$S = \left(\frac{k_i}{k} - 1\right) \ln \frac{r_s}{r_w}$$
(30)

Pressure loss due to skin can also be calculated using

$$\Delta P_{skin} = \frac{q\mu B_o}{2\pi h k_i} S \tag{31}$$

DISCUSSION OF RESULTS

Table 1 shows the composition of the sample used in the simulation, the heptanes plus fractions was divided into pseudo-components using Whitson's method (1983).

Table 2 shows the fluid and reservoir properties used as input in the simulation performed in this study. The simulator was run at varying temperature at first, then at varying pressure also to see the effect of temperature and pressure on the amount of wax precipitated in the reservoir. Results from the program ms are shown in figure 1. Results obtained are validated by comparing with results generated through the use of analytical expression developed by Ring (1991) using the recombined separator liquid and gas whose composition is shown in Table 1 as a case study.

Component	Mole %
Carbon dioxide	7.32
Nitrogen	0.24
Methane	43.7
Ethane	4.75
Propane	5.46
i-butane	0.39
n-butane	1.87
i-pentane	1.32
n-pentane	0.86
hexanes	1.42
Heptanes plus	32.67
	100

Table 1. Composition of the sample used

Table 2. Fluid and reservoir properties used as input in the simulation (Wang et al., 1999)

k _i Initial permeability, md	535	А	0.0
φ_i Initial porosity	0.45	В	0.0
C_{s} = initial saturation of paraffin.	0.0001	η	0.0
Δr, cm	1.0	Mg	13g/g-mole
Δt , year	1.0	ρ_{gsc}	0.00083
Number of blocks	10	Mo	101.73 g/g-mole
Δp , atm	0.68	ρ_{osc}	0.71 g/cm3
ψ , 1/sec	0.0001	M _s	542.7 g/g-mole
β , 1/cm	0.0245	ρ _s	0.85 g/cm3
γ_i , 1/cm	0.0	ΔH_s	25,800 cal/g-mole
μ_o , cp	10	flow rate	0.5ml/min
ρ_s , g/cm3	1.147	C _{si}	5.3%
λ	0.6		
T, oC	50		
B, ibf/ft.SR4	4.3 E-08		
Relative permeability, k _r	0.72		

From the figure 1, it is noticed that the amount of wax precipitated decreases with an increase in temperature of the system. it can be seen that the wax appearance temperature (WAT) predicted from the model is about 305 K. and as the temperature is being reduced the initial increase in wax precipitated is sharp and gradually becoming less pronounced at the temperature below the pour point is passed.

From figure 2, it is seen that the wax weight fraction increases as the reservoir pressure decreases, as predicted by Ring et al.(1994) this phenomenon can be simply attributed to the loss of the lighter ends as the pressure in the reservoir is reduced. Wax precipitation also occurs by reducing the amount of dissolved gas in the liquid phase. Therefore, when the pressure of the reservoir fluid is dropped below the bubble point pressure which is the pressure at which the first bubble of gas leaves the surface of a liquid, the cloud point temperature of the fluid increases and there is a high tendency of wax to form.



Figure 1. Calculated and Experimentally determined weight of precipitated wax at varying temperature.



Figure 2. Wax weight fraction at varying reservoir pressure at a temp. of 300K.

As gas is released from solution with a reduction in gas saturation pressure, shrinkage of the liquid phase would begin to occur which has the effect of increasing the wax composition in the solid-liquid mixture and this causes the wax precipitation to increase as shown in figure 2.

After the precipitation of wax in the reservoir, deposition is the next phase. The result of the deposition of wax is shown in figure 3.



Figure 3. Yearly wax deposition in the porous media at temperature of 300 K.

From figure 3 shown, the amount of wax deposited in the first year was high and after which there was a sudden drop in the volume deposited to almost zero. This phenomenon can

be attributed to fact that it's only at the initial period (i.e. first year) that sizable wax is deposited due to initial high pressure gradient. In the later periods the pressure drop is not enough to cause a sizable wax deposition in the reservoir as the deposited wax must have blocked most of the pore spaces the oil could have occupied thereby reducing the permeability. It is therefore expected that most of the entrapment would occur within the first to the second year of deposition.

If the temperature within the reservoir is further reduced below WAT, there would be a noticeable increase in the amount of wax that would be deposited again because more wax is being precipitated. Figure 4 below shows the yearly wax deposited over ten years in the reservoir at a temperature of 300K. A sharp decrease was noticed between the second and fourth year. This can be attributed to fact that it's only at the initial period (i.e. first year down to the second year) that sizable wax is deposited due to initial high pressure gradient as a result of high velocity of the fluid in the reservoir due to relatively high permeability to the fluid during this period. In the later periods the pressure drop is not enough to cause a sizable wax deposition in the reservoir. It is therefore expected that most of the entrapment would occur within the first to the second year of deposition.

The wax deposited at varying distance (radius) from the wellbore is shown in figure 5. It can be seen that wax particles do not deposit much in the reservoir, this is due to lower pressure gradient in the reservoir, sizable amount of wax only deposit close to the well-bore where the pressure gradient is high This agrees with J N Ring et al. (1994) observation, that wax deposition is a near well-bore phenomenon.



Figure 4. Yearly wax deposition in the reservoir at 300 K for 10 years period.



Figure 5. Amount of wax deposited with distance.

The model was validated with Ring (1991) analytical was deposition expression in the literature. The was deposited profile was noticed to follow the same profile to that predicted through the use of the analytical expression by Ring (1991) this is shown in fig. 6, the differences was due to the assumption among others of the constant porosity during deposition in the development of the Ring (1991) analytical expression which is too drastic assumption in a typical petroleum reservoir.

Despite the assumption the deposition profile still follows same trend (though with relatively higher percentage of predicted deposition wax) with the simulated results in figure 5.



Figure 6. Amount of wax deposited with distance from Ring, 1991 Analytical expression.

As expected, the skin effect recorded though little was greatest at the near wellbore region. This is because the solid paraffin continues to buildup near the wellbore and production rate declines, therefore the most damage is done near the wellbore and that is also where there is a considerable decrease in the permeability of the reservoir to fluid flow. The skin caused by the paraffin deposition can be removed by electrical heating. This would increase the rate of oil production from the reservoir and also reduce the oil viscosity near the wellbore. Figure 7 shows the skin effect in the reservoir case being considered, it was observed that the skin effect decreases with time due to reduce in wax deposition with time.



Figure 7. Skin effect in the reservoir with time.

Figure 8 shows the variance of skin with reservoir distance, it can be seen that some appreciable effect is felt at the wellbore. The reduction in permeability recorded in this study is shown in figure 9. The figure closely agreed to that obtains by Wang et al. (1999). The reduction in permeability is attributed to the deposition of the precipitated wax in the pore spaces of the reservoir. As shown by the figure, the rate of permeability reduction increases near the well-bore where the effect of paraffin deposition is at its maximum. At the point where the effect of paraffin deposition ceases to be significant, the permeability reduction in the reservoir would cease and the rate tends to becomes constant.



Figure 8. Skin effect at varying distance in the reservoir after 1 month.



Figure 9. Reduced permeability at varying distance in the reservoir after 1 month.

The productivity ratio defined as the ratio of the productivity index at the instant to the initial productivity index is shown in figure10 below.



Figure 10. Variation of productivity ratio with time in years in the reservoir.

The figure shows the decline expected to be obtained in the reservoir due to the reduction in permeability and the skin damage recorded. These factors reduce the productivity index from that at the initial condition to a new state. The rate of decline increases as the number of years increases. It is advised that this reservoir should be stimulated to get the production of oil back to the initial if this is found economical.

CONCLUSION

The approach taken in this study adequately describes and simulates deposition of paraffin in a petroleum reservoir. The precipitation and consequently deposition was shown to be a near well-bore phenomenon where the pressure gradient is relatively higher than those attainable far in the reservoir. Though little, the paraffin deposition was shown to cause decrease in the porosity, permeability and consequently higher skin in the porous medium especially near the well-bore region. Frequent stimulation by heat treatments of the near wellbore region is recommended for wells which produce high waxy crude so as to neutralize the skin effects cause by wax deposition in the region.

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