Dynamic Experimental Study on the Paraffin Deposition Prevention Performance of Tungsten Alloy Coating Pipe in Simulating Vertical Wellbore

Ying Sun,* Shuxia Li,* Renyuan Sun,* Qiang Zhang, Bowen Zhang, and Yuxiang Wei

ABSTRACT: In this study, a self-designed apparatus was used to provide a quantitative evaluation of the wax prevention effect of tungsten alloy-coated tubing compared with ordinary tubing in oil production. The paraffin deposition of both pipes at different temperatures and different flow rates was studied. The efficiency of paraffin deposition prevention of the tungsten alloy coating pipe was analyzed. The results show that using this apparatus can efficiently and accurately calculate the wax prevention rate and can accurately obtain the wax deposit and wax thickness of the inner wall. The paraffin deposition of both pipes reaches the highest point at 290.15 K, and it reduces with the increase of flow rate. The use of the tungsten alloy coating pipe results in about 30% reduction in paraffin deposition. It provides a promising method for the paraffin inhibition to extend the wax removal cycle.

1. INTRODUCTION

Paraffin is a heavy molecular weight, complex molecule which mainly contains carbon and hydrogen atoms. The conditions of the crude oil are altered with the changes of temperature and/or pressure and evaporation of lighter hydrocarbon fractions, and paraffin solidifies and separates from the liquid phase and deposits on the surfaces of pipes.1 This deposition leads to decreased production and mechanical problems.2

Techniques have been devised to control paraffin deposition in a wellbore:3−7

- Mechanical treatments.
- Thermal treatments.
- Bacterial treatments.
- Chemical treatments.
- Coating treatments

As the oldest method, mechanical treatments are easy to accomplish, but the inside surface wears out as the scrapers cut the deposit, and it will intensify the deposit of paraffin.7

Thermal methods are usually carried out by injecting hot oil down the wellbore. Some studies7 indicate that particulates and chemicals in the injecting fluid have potential to damage the formation. Moreover, formation can no longer be mobilized by the heat available through hot oiling, which tends to build up deposits of very hard wax.

Bacterial treatment is limited to wells that produce water and has a bottom hole temperature below 93 °C because the microbes which are introduced into the wellbore to produce chemicals that inhibit wax production and to break down the produced waxes require water to survive and cannot tolerate high temperatures.

Chemical treatment which includes solvents, dispersants, surfactants, and wax crystal modifiers is very successful for the control of paraffin precipitation and deposition. However, it was observed that no single chemical was equally effective in all wells, and hence it is required to find the best inhibitor for each well individually. Also, chemical treatment is costly and highly toxic.10

As it has been proved that the rate of deposition of paraffin is related to surface properties of the pipeline wall,11,12 using a smooth coating pipe with a low free surface energy could reduce the deposition of paraffin.

In the last decade, efforts have been devoted to developing coating materials. Coating materials can be divided into three kinds: polymer coating, glass coating, and alloy coating. The water-wetting property of glass is the key factor controlling the deposition. When the water content of the oil is more than 60%, the deposition on the wall of the glass pipe is reduced, and the fragility of glass will affect the life of the pipes.13

Experiments on polymer coating have been conducted by a

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number of authors.\textsuperscript{14,15} Plastic shows promise in paraffin inhibition, which is indicated in a study in 1957.\textsuperscript{16} Zhang et al.\textsuperscript{17} studied drag reduction and paraffin deposition prevention of eight coatings by a rotation viscometer and cold spot and found that the low surface energy of fluoroethylene polymer, silicone rubber, and methyl acrylate–styrene copolymer coatings has an obvious effect on drag reduction and paraffin deposition prevention. Quintella et al.\textsuperscript{18} indicated that polypropylene is better suited to inhibit wax deposition than high-density polyethylene and EVA28 under a high flow rate for heavy crude oil. Polymer coating solves many problems, though it has limitations regarding maximum operating temperature and creep life.\textsuperscript{19} Shao et al.\textsuperscript{20} reported that rare earth elements can influence the wetting behavior of materials. Wang et al.\textsuperscript{21} studied the wetting behaviors of bare and modified powder zinc by capillary rise experiments to evaluate the paraffin prevention performance. The zinc-rich coating can be a good candidate for paraffin prevention. Alloy coating has an advantage in high-temperature resistance and wear resistance over polymer coating. These alloy coating pipes get smoother surfaces and lower free surface energy, and their features are the key to paraffin inhibition. An alloy coating that was prepared by thermal spraying and followed by inorganic salt sealing treatment proved that more than 90% paraffin wax inhibition rate is achieved. The catalytic components in the alloy coating and the novel microstructure of its surface attribute to the high inhibition performance. Lanthanum-modified zinc powder can also be a good candidate used for zinc-rich coatings to prevent the deposition of paraffin.\textsuperscript{22} Paraffin is one kind of nonpolar molecule, and the paraffin motion shifts to directional movement when it is affected by the magnetic field created by the strontium ferrite.\textsuperscript{23}

The purpose of this paper is to introduce a kind of tungsten alloy coating pipe and discuss the paraffin deposition prevention performance by measuring the paraffin accumulation of the coating pipe and the normal steel pipe at the same conditions; moreover, the reliability of the self-designed equipment is verified.

2. RESULTS AND DISCUSSION

2.1. Paraffin Deposition versus Temperature. Figure 1 shows the results of the change of differential pressure (DP) in experiments in which the temperature is 287.15, 290.15, 293.15, 296.15, and 299.15 K, the flow rate of the oil was held constant at 3 L/min, and the trend of pressure fluctuation was the same.

As shown in Figure 2 which is drawn according to the calculation results, the deposition in both pipes reaches the highest point at 290.15 K. When the temperature is below this point, the shear stress increases, and slower molecular motion affects the migration and accumulation of the paraffin molecules. The paraffin molecules can hardly nucleate above that temperature. The paraffin deposition of the tungsten alloy coating pipe is less than that of the normal steel pipe.

2.2. Paraffin Deposition versus Flow Rate. The five experiments with different flow rates (2, 2.5, 3, 3.5, and 4 L/min) were conducted, and the temperature of the oil was held constant at 290.15 K. The results of experiments show the same trend of pressure fluctuation as the previous experiments. Figure 3 shows the results of the DP when the flow rate is 2.5 L/min.

2.3. Dynamics of Paraffin Deposition versus Pressure. Figure 4 shows that the paraffin deposition reduces with the increase of flow rate. The paraffin molecules separate from the liquid phase, if the flow rate is high, and the paraffin gets less time to deposit on the surfaces of pipes. The high shear stress

![Image](https://dx.doi.org/10.1021/acsomega.0c03002)
and the high flow rate remove the deposition which has been formed.

2.3. Efficiency of Paraffin Deposition Prevention. We analyzed the efficiency of paraffin deposition prevention of the tungsten alloy coating pipe. The number (shown in Table 1) can reach to about 30%. The tungsten alloy coating pipe has smooth surfaces and low free surface energy, that is, the surfaces are hardly wetted by the paraffin. Moreover, the polarization of the tungsten alloy coating pipe surface is more powerful than the normal steel pipe; the paraffin is a kind of nonpolar molecule, and the adsorption capacity between the coating pipe surface and the paraffin is lower.

2.4. Paraffin Deposition Profile. After the last experiment (290.15 K, 2.0 L/min), the two pipes are taken down, and the thickness of the paraffin deposition is measured at different points (shown in Figure 5). Then, we get the effective thickness of the tungsten alloy coating pipe and the normal steel pipe, and they are 4.3 and 6.1 mm, respectively. Therefore, the efficiency of paraffin deposition prevention is 27.6%, and it is within the limits of experimental error (3.29%).

3. CONCLUSIONS

1) The self-designed equipment is reliable to simulate the crude oil flow in the vertical wellbore. With this equipment, we can carry out dynamic simulation experiments on the flow conditions in the wellbore and paraffin inhibition of different coating materials.

2) The paraffin deposition of the tungsten alloy coating pipe is less than that of the normal steel pipe at all experimental temperatures, and the deposition of both pipes reaches the highest point at 290.15 K.

3) Paraffin deposition reduces with the increase of flow rate under experimental conditions. The paraffin deposition of the tungsten alloy coating pipe is less than that of the normal steel pipe at all experimental flow rates.

4) These features of the tungsten alloy coating pipe, which are the smooth surface, low free surface energy, and polarization, contribute to the paraffin inhibition. The efficiency of paraffin deposition prevention reaches about 30%. This result is verified by measuring the thickness of the paraffin deposition. The experimental error is 3.29%.

4. EXPERIMENTAL SECTION

4.1. Materials. The internal and outside diameter of the pipes is 38.1 and 54 cm, respectively. For purposes of comparison, one of the pipes was coated with the tungsten alloy, and the center average value of roughness is Ra = 0.536 ± 0.02 μm. Another is the normal one, and the center average value of roughness is Ra = 0.391 ± 0.02 μm.

The test crude oil was produced from the Xinjiang oil field in China. The components of the representative oil sample are listed in Table 2.

| Table 2. Components of the Oil Sample |
|--------------------------------------|
| components parameter                |
| saturated hydrocarbon (%)           | 56.13 |
| aromatics hydrocarbon (%)           | 8.37  |
| resin (%)                           | 1.09  |
| asphaltene (%)                      | 0.43  |
| wax (%)                             | 19.13 |
| water (%)                           | 0.82  |

The density of the oil is 807.2 kg/m³ at 293.15 K. Viscosity was measured using an Anton Parr viscometer. The correlation between viscosity and temperature can be determined by the formula

\[ \mu = 5.76 \times 10^{-6} T^2 + 0.96 T + 74530.6 \]  

where \( \mu \) is the viscosity, mPa·s; \( T \) is the fluid temperature, K.

The wax appearance temperature measured with a differential scanning calorimeter (DSC) by Total Fina Elf was 303.15 K at atmospheric conditions (Figure 6).

4.2. Apparatus. This apparatus shown in Figure 7 is designed to simulate the flow of crude oil in vertical wellbores during crude oil production. This apparatus includes provisions for maintaining a constant temperature and flow rate. The DP sensor is connected with the test pipe to record the pressure difference between the two ends of the pipe. Then, the data is analyzed to get the paraffin deposition prevention performance.

The innovation of this apparatus is to provide a quantitative evaluation method for the wax prevention effect of tungsten alloy coated tubing compared with ordinary tubing in oil production. Using this apparatus can efficiently and accurately calculate the wax prevention rate and can accurately obtain the
wax deposit and wax thickness of the inner wall, which provides a reference for the schedule of the wax removal cycle. The apparatus can intuitively evaluate the wax control efficiency of paraflin wax and provide a reference for oilfields to determine wax removal and control measures.

4.3. Calculations. When fluid flows in the pipe, there exists a pressure difference between both ends of pipe because of flow resistance. The pressure is closely related to multiple factors such as viscosity, density, flowmeter, inside diameter, and outside diameter of the pipe. The pressure increases because of a decrease of the internal diameter due to the paraffin deposit on the surface when the pipe inner surface temperature goes below the wax appearance temperature of the oil.

The equation for the friction loss along the pipe under laminar flow is given as

\[ h_f = \lambda \frac{L \nu^2}{D g} \]  \hspace{1cm} (2)

where \( h_f \) is the head loss due to the flow resistance, \( m; \) \( \lambda \) is the Darcy–Weisbach coefficient; \( L \) is the pipe length, \( m; \) \( D \) is the pipe diameter, \( m; \) \( \nu \) is the average velocity, \( m/s; \) \( g \) is the gravitational acceleration, 9.8 m/s².

The friction loss can be expressed as the pressure drawdown between both ends of the pipe

\[ h_f = \frac{\Delta P}{\rho g} \]  \hspace{1cm} (3)

where \( \Delta P \) is the pressure drop, kPa; \( \rho \) is the density, kg/m³.

Equation 1 is substituted in eq 2 to obtain eq 4. The net diameter can be calculated by

\[ D = \lambda \frac{\rho L \nu^2}{2 \Delta P} \]  \hspace{1cm} (4)

For laminar flow, the Darcy–Weisbach coefficient (\( \lambda \)) is only a function of the Reynolds number (\( Re \)) and is independent of the surface roughness of the pipe

\[ \lambda = \frac{64}{Re} \]  \hspace{1cm} (5)

\[ Re = \frac{\rho Q}{\pi \mu D} \]  \hspace{1cm} (6)

where \( Re \) is the Reynolds number; \( Q \) is the flow rate, m³/s; \( \mu \) is the viscosity, mPa/s.

Then, the volume of paraffin deposition can be calculated by

\[ m = \rho L \pi (D_0^2 - D_1^2) \]  \hspace{1cm} (7)

where \( m \) is wax deposition, kg; \( D_0 \) is the initial diameter, \( m; \) \( D_1 \) is the diameter with paraffin deposit, \( m. \)

Equation 7 can be used to determine the efficiency of paraffin deposition prevention.

\[ E = \frac{m_n - m_l}{m_n} \times 100\% \]  \hspace{1cm} (8)

where \( E \) is the efficiency of paraffin deposition prevention; \( m_n \) is the wax deposition of ordinary tubing, kg; \( m_l \) is the wax deposition of tungsten alloy coated tubing, kg.

- **AUTHOR INFORMATION**

Corresponding Authors

Ying Sun — School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, China; orcid.org/0000-0002-5398-9815; Email: sunying009@outlook.com

Shuxia Li — School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, China; Email: lishuxia@upc.edu.cn

Renyuan Sun — School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, China; Email: sunrenyuan@126.com

Authors

Qiang Zhang — Jiangsu Gas Storage Branch Company of Huabei Petroleum Administration, Changzhou 213200, China

Bowen Zhang — Jiangsu Gas Storage Branch Company of Huabei Petroleum Administration, Changzhou 213200, China

Yuxiang Wei — School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c03002

**Notes**

The authors declare no competing financial interest.

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