Wax Deposition Law under a Gas−Liquid Bubbly Flow Pattern

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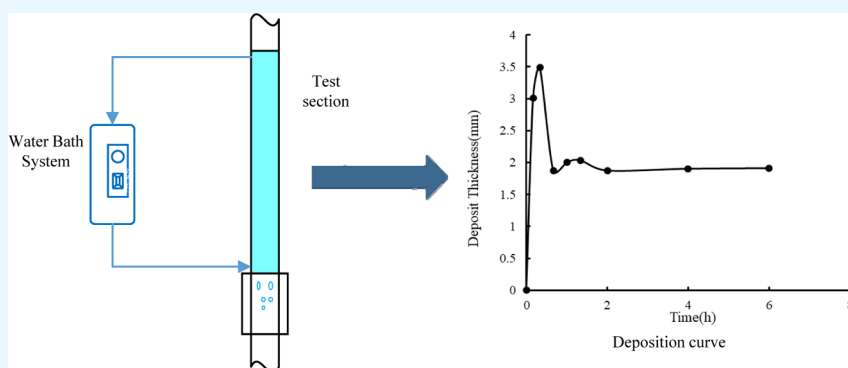
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ABSTRACT: Under the high-pressure and low-temperature environment of the deep sea, wax deposition will occur in the wellbore. This study discusses the effect of gas−liquid two-phase bubbly flow on wax deposition. In this study, wax deposition experiments of a gas−liquid two-phase flow in vertical pipelines were carried out using waxy white oil and air as the experimental medium. The results show that under the bubble flow pattern, within a short period of time from the start of wax deposition, it rapidly accumulates to the peak, then rapidly cuts off part of it, and then presents a simple harmonic dynamic trend until the final stability. The average wax-deposit thickness decreases first and then increases with the increase of superficial gas velocity, and it increases first and then decreases with the increase of superficial liquid velocity. The average wax-deposit thickness decreases with the increase of oil temperature. The average wax-deposit thickness was substantially constant and then decreases with the increase of ambient temperature. The wax-deposit thickness increases with the increase of wax content in oil flow. This research is useful for people to further understand the changes in the wax deposition process.

1. INTRODUCTION

In the process of petroleum production, the pipe diameter decreases with the buildup of wax deposits. Limited by the actual flow area of the wellbore, the production of the well is reduced and the pumping cost is increased.[1−5] If the deposits are not removed in time, it may even threaten the safety of transmission in serious cases.[6−9] Wax deposition has always been a hot issue in the field of petroleum exploration and the development and pipeline transportation. Detailed research has been conducted on it by scholars for many years. The wax deposit is similar to a mixture of porous media containing a large amount of condensate oil.[10,11] Through the study of wax deposition in pipelines, the wax-deposition mechanism summarized by scholars includes molecular diffusion, shear dispersion, Brownian diffusion, gravity settling, shear stripping, and aging.[12,13] Among them, molecular diffusion is considered as the main mechanism of wax deposition.[14]

Burger et al.[15] first proposed the mechanisms of molecular diffusion, shear dispersion, and Brownian diffusion in 1981 for wax deposition and constructed a semiempirical model of wax deposition. Burger believed that molecular diffusion dominates

at higher temperatures and shear dispersion is more pronounced at lower temperatures. In 1988, Weingarten and Euchner[16] first measured the deposition rate caused by molecular diffusion through an original experimental device and indirectly obtained the deposition rate caused by shear dispersion. Hamouda and Davidsen[17] analyzed the field data and conducted related simulation experiments and concluded that molecular diffusion is the main mechanism of wax deposition and shear dispersion is effective only at low temperatures. In 1996, Hsu et al.[18−20] studied the wax deposition of waxy crude oil under turbulent conditions. It was found that the hardness and the carbon number of wax deposited on the wall increased with the increase of deposition duration. In the formation and aging of the gel layer, Singh et al.[21−23] found that aging is a phenomenon of

counter-diffusion in which wax molecules diffuse into the gel deposit and oil molecules diffuse out, resulting in an increase in the wax content of the deposit.

The study of multiphase flow was carried out later than the single-phase flow wax deposition problem. At present, most research studies on multiphase flow are based on single-phase flow research. Based on the mechanism of single-phase flow wax deposition, the wax deposition characteristics in multiphase flow were analyzed and the construction modification of the multiphase flow wax deposition model was carried out. Multiphase flow studies have focused on oil–water or gas–liquid two phases in horizontal sections, with less research on vertical tube flow. Forsdyke[24] believes that the study of multiphase flow wax deposition should follow the experimental method of single-phase flow wax deposition, considering the influence of the flow state on the thickness of wax deposition under different flow patterns. Matzain et al.[25] and Nilufer[26] conducted a loop experiment on the relationship between two-phase gas–liquid flow wax deposition and flow pattern and obtained a similar conclusion—the upper wax deposition of the pipeline under the intermittent flow type is thicker and softer. However, the number of experimental groups was small and no detailed deposition law was obtained. Yu[27] carried out the stratified flow and intermittent flow tests to analyze the deposition law, mainly to study the influence of the relative conversion rate of gas and liquid on the wax-deposit thickness. However, he considered fewer influencing factors and did not conduct a detailed study of the entire deposition process.

At present, the research of scholars mainly focuses on two-phase gas–oil stratified flow wax deposition in the horizontal loop, while the research on two-phase gas–oil wax deposition in the vertical pipeline is relatively small.[28−30] Wax deposition of two-phase gas–oil flow is a very complex process, which is affected by oil flow composition, flow rate, temperature, wall roughness, and so forth.[31] The problem is extremely complicated and requires in-depth experimental research. Therefore, this paper further explores the deposition law and related influencing factors of two-phase gas–oil bubbly flow in the vertical pipeline through the indoor simulation of two-phase gas–liquid flow wax deposition experiment.

2. TEST DEVICES AND METHOD

2.1. Test Medium and Loop. The oil used in the test is Industrial white oil no. 7, which is a kind of mineral oil. The manufacturer of the mineral oil is Moroke. The no. 58 fully refined paraffin wax was used in the experiment with the melting point ranging from 58 to 60 °C and the carbon number distribution is mainly concentrated between C_{22} and C_{28}. By adding refined wax to dissolve, the wax content of the oil is 8%. The inlet temperature of the test tube section was maintained at about 50 °C. At this time, the density of the oil sample was 802 kg·m^{-3}, and the wax appearance temperature (WAT) of the oil sample was 34 °C. The WAT is obtained by using a differential scanning calorimeter. The viscosity–temperature curve measured by a high-temperature and high-pressure rheometer is shown in Figure 1.

The vertical loop device for wax deposition is made of a DN25 stainless-steel pipe and consists of an oil supply system, gas supply system, observation window, test section, measurement system, and temperature control system. The loop experiment process is as follows: starting from the oil tank, pumping the waxy oil into the loop through the oil pump, injecting air into the loop under the test section through the air compressor; the
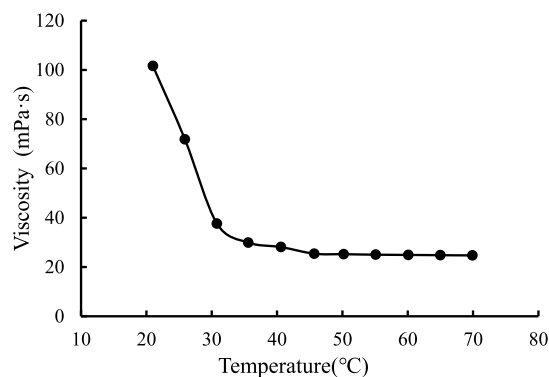

Figure 1. Viscosity temperature curve of waxy 8% simulated oil (200 rpm).

water bath system provides a low-temperature environment outside the pipe wall of the test section, a thermometer is installed at each entrance of the section to monitor the temperature of the fluid in real time; and finally, the oil flow is recycled back to the oil tank for gas–liquid separation (Figure 2).

The length of the loop test section is 2 m, and a transparent observation window is arranged below the test section to facilitate the observation of the flow pattern change of the gas–liquid two-phase flow (Figure 3). The water bath system keeps cooling to maintain the temperature of the cold water outside the whole test tube section. The loop is capable of performing wax deposition tests under the single-liquid phase and two-phase gas–liquid flow conditions in a vertical pipe. The loop can be used to study the effects of the gas–liquid phase conversion rate, wall temperature, oil temperature, and wax content on wax deposition.

2.2. Experimental Method. The waxy white oil in the oil tank was heated, the oil pump was turned on to deliver oil to the loop, and the flow of the oil was observed through the observation window. When the temperature of the oil flow inlet of the test part is stable, the gas flow meter and shut-off valve to pass were opened in a certain flow of gas, and then the water bath cycle of the test part was opened. At the same time, the data acquisition software was used to record the temperature change of the test section oil outflow inlet in real time. In the test, the superficial liquid velocity (v_{sl}) was adjusted by a pump, and the superficial gas velocity (v_{sg}) was adjusted by a gas flow meter.

The pipe diameter is measured before starting the test. When white oil was injected into the test pipe section, the quality of the injected oil (ΔM) and the pressure change caused by the oil column (ΔP) were recorded. The calculation of pipe diameter is as follows

$$D = \sqrt{\frac{4\Delta M \times g}{\pi \Delta P}} \tag{1}$$

where D is the diameter of the test section, m, and g is the acceleration of gravity, m·s^{-2}. This method is also used to measure the thickness of the wax layer.

3. RESULTS AND DISCUSSION

Different from the previous single-phase flow tests, this test not only explores the influencing factors of wax deposition but also focuses on the curve of the thickness of wax deposits with time.

3.1. Wax Deposition Process. Figure 4 shows the change in wax-deposit thickness at different test times. It can be seen
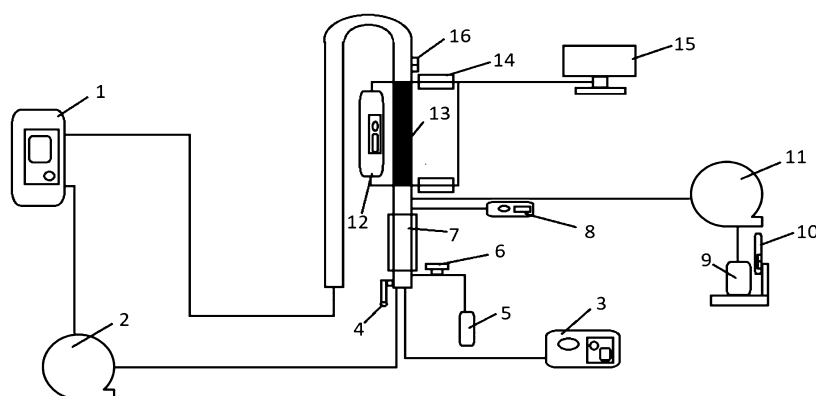
Figure 2. Schematic diagram of the experimental loop of gas−liquid two-phase flow wax deposition. (1) Tank; (2) oil pump; (3) air compressor; (4) ball valve; (5) water scoop; (6) valve; (7) observation window; (8) pressure gauge; (9) oil drum; (10) electronic scale; (11) oil injection pump; (12) water bath system; (13) test section; (14) thermometer; (15) computer; and (16) bolt.

Figure 3. Observation window.

from the results of multiple sets of experiments that for a low-temperature vertical pipe flow, the process of wax deposition can be summarized as follows: within a short time of the beginning of wax deposition, it quickly accumulates to the peak and then shears off a part of the wax deposition layer. Then, the thickness of the wax deposition layer will fluctuate up and down until it finally stabilizes. For the variation of wax deposition thickness with time, the reasons are as follows:

(1) The wall temperature is much smaller than the WAT, that is, the radial temperature gradient between the pipe wall and the oil flow is large, resulting in a large amount of wax deposits in the initial stage. In addition, a large amount of condensate oil is incorporated in the pores of the initial deposit, and the overall strength is not high. Due to the accumulation of wax deposits, the flow cross section of the test pipe section becomes smaller. On the one hand, the relative flow rate of the fluid becomes larger, which leads to an increase in the shear force on the surface of the wax-deposit layer. When the shear force on the surface of the deposited layer is greater than the strength of the deposited layer, the deposit is sheared off. On the other hand, because the initial deposition layer is soft, when hot oil flows over the surface of the deposition layer, a part of the surface deposit will melt. This is the reason why the wax deposition layer accumulates rapidly in a short time, and the thickness of the wax deposition layer fluctuates sharply in the initial stage.

(2) The wax molecules are affected by the temperature gradient and continuously migrate to the tube wall until the crystals are precipitated. Affected by the aging mechanism, the wax molecules will diffuse into the interior of the sediment layer and replace the condensate oil encapsulated in the sediment layer. This process leads to a decrease in the oil content in the sediment layer and an increase in the wax content, and the condensate in the sediment is continuously replaced by wax crystals. Throughout the process, these two effects simultaneously affect the thickness of the wax layer until equilibrium is reached. Therefore, as time goes by, the thickness of the wax layer tends to stabilize.

(3) After 2 h of wax deposition, the thickness of the wax deposition layer stabilized. The reason is analyzed as follows: affected by the aging mechanism, the strength of the wax-deposit layer increases, and it is not easy to be washed and sheared by the oil flow. In addition, due to the presence of the wax deposition layer, the radial temperature gradient at the solid−liquid interface is small, the heat exchange efficiency between the oil flow and the external environment and the radial driving force of the wax crystals is reduced, so the thickness of the wax deposition layer is difficult to further increase.

3.2. Effect of v_{sg} on Wax Deposition. In the test process, based on the SH-I hydrate (wax) multiphase flow high−pressure-loop experimental software, the temperatures of the inlet and outlet oil samples of the test pipe section were recorded in real time. The measured data of the experiment are shown in Table 1.

It can be seen from Table 1 that the axial temperature gradient of the single-phase flow is much larger than the axial temperature
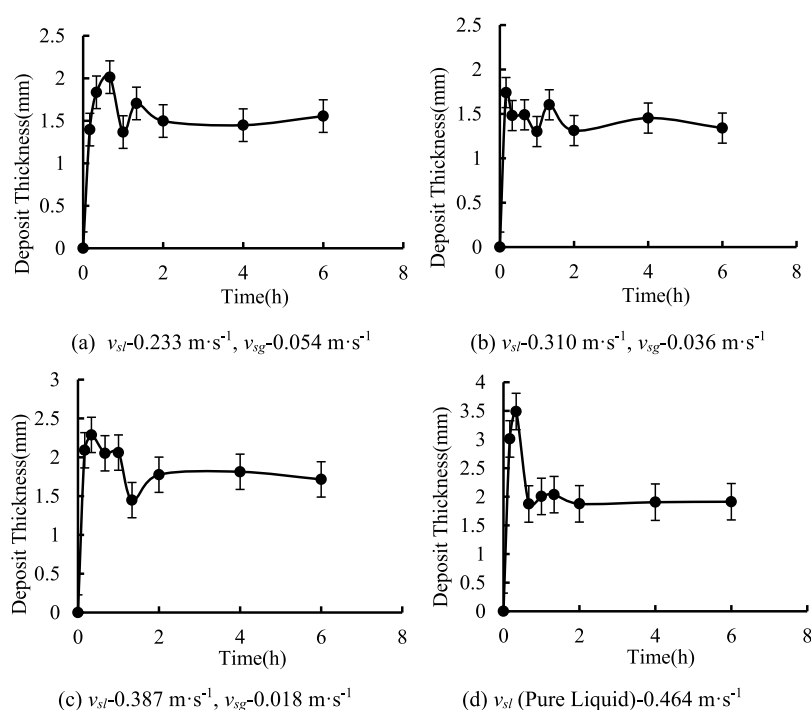
(a) v_{sl}-0.233 m·s⁻¹, v_{sg}-0.054 m·s⁻¹   (b) v_{sl}-0.310 m·s⁻¹, v_{sg}-0.036 m·s⁻¹

(c) v_{sl}-0.387 m·s⁻¹, v_{sg}-0.018 m·s⁻¹   (d) v_{sl} (Pure Liquid)-0.464 m·s⁻¹

Figure 4. Wax deposition curve in a low-temperature environment.

Table 1. Test Pipe Section Inlet and Outlet Temperature Data

vsl/m·s−1	vsg/m·s−1	Tin/°C	Tout/°C	ΔT/°C
0.233	0.000	51.2	30.9	20.3
	0.018	50.7	44.1	6.6
	0.036	50.8	43.6	7.2
	0.054	50.0	43.5	6.5
0.310	0.000	51.7	32.0	19.7
	0.018	51.6	45.2	6.4
	0.036	51.7	45.1	6.6
	0.054	50.7	44.5	6.2
0.387	0.000	51.4	31.7	19.7
	0.018	51.2	44.8	6.4
	0.036	49.9	42.7	7.2
	0.054	50.9	44.4	6.5
0.464	0.000	51.5	32.6	18.9
	0.018	51.3	45.0	6.3
	0.036	52.6	46.0	6.6
	0.054	51.3	45.0	6.3

gradient of the gas−liquid two-phase flow, that is, the heat loss is large when the oil flow is pure liquid phase. The reason is analyzed as follows: the thermal conductivity of air is much smaller than the thermal conductivity of oil. When air is mixed into the oil flow, the low thermal conductivity of air plays a role and to a certain extent, it acts as a heat preservation for the oil flow. Therefore, the axial temperature difference of the gas−liquid two-phase flow is much smaller than the axial temperature difference of the unidirectional flow. In the gas−liquid two-phase flow of the wellbore, the low thermal conductivity of the air inhibits the precipitation of the wax crystal to a certain extent, resulting in a decrease in the average wax layer thickness.

Under the premise of constant v_{sl}, single liquid phase and two-phase gas−oil wax deposition experiments were carried out by changing the amount of gas introduced. Figure 5 shows that when the v_{sl} is constant, the average thickness of the wax

deposition layer decreases first and then increases as the v_{sg} increases.

The reasons for this phenomenon are analyzed as follows:

(1) Under the same v_{sl}, the deposit thickness of two-phase gas−oil flow is significantly smaller than that of the single liquid phase. On the one hand, after the oil flows into the gas, it is affected by the shearing action of the gas, and the flushing action of the oil flow is enhanced; on the other hand, because the thermal conductivity of the gas is smaller than the liquid, the axial temperature difference of the oil flow in the test tube section is reduced, that is, the average temperature of the oil flow is high and the wax crystal is not easy to precipitate. Therefore, the increase in the gas phase suppresses the precipitation of the wax crystal to some extent.

(2) As the gas flow rate further increases, the thickness of the wax-deposit layer tends to increase further. As the liquid volume fraction in the unit oil-flow volume decreases, the actual flow velocity of the liquid phase increases and the convective heat transfer between the oil flow and the wall surface is strengthened. The heat preservation effect of the gas is mainly reflected in the maintenance of the oil-flow temperature in the central portion of the pipeline. The portion of the fluid that is in direct contact with the tube wall cools significantly. Therefore, the radial temperature difference near the wax-deposit layer will increase, providing power for the radial migration of the wax molecules, and the wax crystals are more likely to precipitate.

3.3. Effect of v_{sl} on Wax Deposition. When discussing the influence of v_{sl} on wax deposition, v_{sg} is kept constant, and the v_{sl} is changed. The deposition tests of the single liquid phase and two-phase gas−liquid flow are carried out, respectively.

Figure 6 shows that for the single liquid phase and bubbly flow, the average thickness of wax deposit increases first and then decreases with the increase of v_{sl} under certain conditions of v_{sg}.
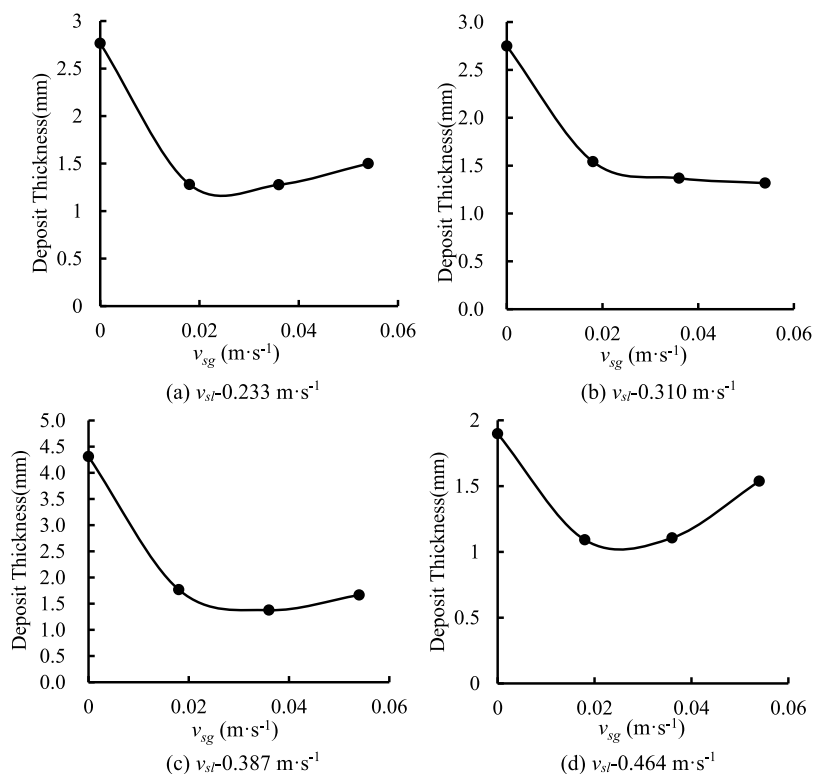
Figure 5. Curve of the average wax-layer thickness as a function of v_{sg}.
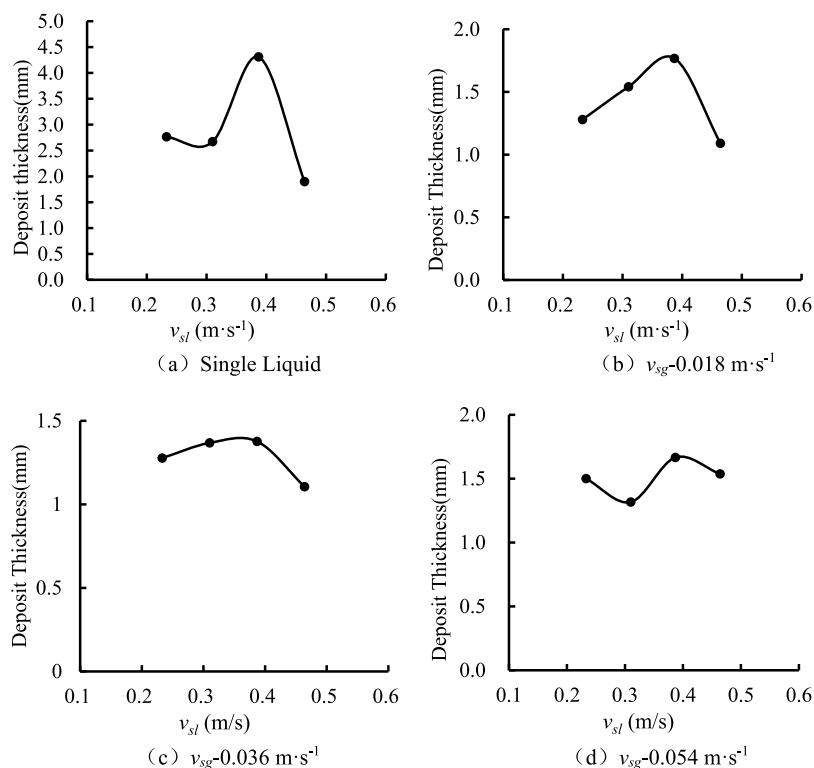

Figure 6. Curve of average wax-layer thickness with v_{sl}.

For the above phenomenon, the specific analysis is as follows:

(1) Compared with single-phase oil flow, the wax deposition thickness of two-phase gas−oil flow is generally smaller. The reason is that the heat transfer efficiency of two-phase gas−oil flow is lower than that of single-phase oil flow, so

the amount of wax molecules precipitated is relatively small.

2 For bubbly flow, the v_{sg} is constant. With the increase of v_{sl}, the convective heat transfer between the oil flow and the pipe wall is intensified and the radial temperature

gradient near the sediment layer increases, which provides the driving force for the radial migration of the wax crystal molecules, so the thickness of the wax-deposit layer increases. In addition, the increase of v_{sl} leads to an increase in the liquid hold-up rate in the test pipe section, and the contact area and contact time between the oil flow and the pipe wall increase, so the wax-deposit layer has a tendency to increase.

(3) When the v_{sg} is constant, as the v_{sl} is further increased, the shear stress at the pipe wall becomes larger. Therefore, the cutting action on the surface of the wax-deposit layer is strengthened, and the deposit is thus peeled off.

3.4. Effect of Oil Temperature on Gas−Liquid Two-Phase Wax Deposition in the Wellbore.
When v_{sl} equals 0.464 m·s^{-1} and v_{sg} equals 0.018 m·s^{-1}, the oil temperature is changed to perform a wax deposition test. In the test, the temperature at the inlet of the test pipe section was controlled by adjusting the oil tank heating device to be 46, 50, and 54 °C, respectively.
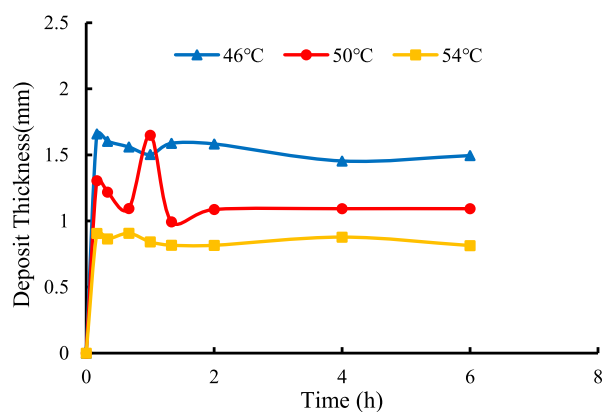

Figure 7. Wax deposition curves at different oil temperatures.

According to Figure 7, it can be intuitively found that as the oil temperature increases, the thickness of the wax-deposit layer decreases when it is stable. The reasons are as follows:

(1) When the temperature of the oil flow increases, the temperature difference between the pipe wall and the oil flow increases, that is, the radial temperature gradient near the interface of the wax-deposit layer increases, which provides a stronger power for the radial migration of the wax molecules. Therefore, to a certain extent, the deposits are more likely to accumulate.

(2) As the temperature of the oil stream increases, the temperature near the surface of the wax layer increases as well. The ability to dissolve wax at the solid−liquid interface increases, resulting in a decrease in the thickness of the wax layer. Therefore, when the oil temperature changes, the trend of the average wax layer thickness depends on which of the above two effects is greater.

3.5. Effect of Ambient Temperature on Gas−Liquid Two-Phase Flow Wax Deposition in the Wellbore.
The two-phase gas−liquid flow with a v_{sl} of 0.464 m·s^{-1} and a v_{sg} of 0.018 m·s^{-1} was studied. In the test, the temperature of the water bath represent the ambient temperature and the temperature of the water bath is set at 4, 8, and 12° C, respectively.

The test results are shown in Figure 8. When the pipe-wall temperature is low, the average wax layer thickness of the two-
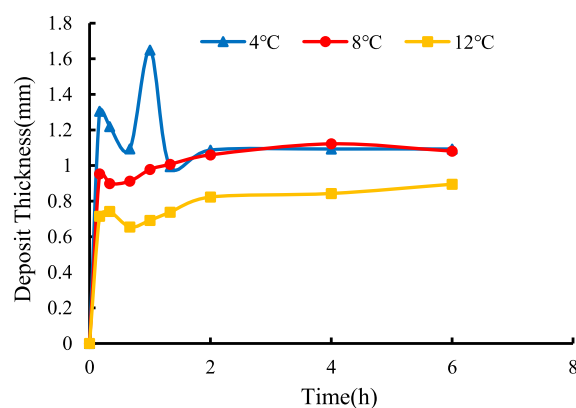

Figure 8. Wax deposition curves at different wall temperatures.

phase gas−oil flow is basically unchanged and then decreases with the further increase of the pipe-wall temperature.

The reasons for this phenomenon are as follows:

(1) When ambient temperature decreases, the temperature difference between the pipe wall and the oil flow becomes larger, and the radial migration power of the wax molecules increases. Therefore, in the early stages of deposition, the smaller the ambient temperature, the greater the amount deposited.

(2) When the molecular weight of the precipitated wax reaches an equilibrium with the amount of the deposit sheared off by the oil flow, the thickness of the wax layer is substantially unchanged. When the gas−liquid phase conversion speed is constant, the oil flow has a constant flushing effect on the wax-deposit layer. Due to the increase in temperature, the oil stream has an enhanced ability to dissolve wax. When the temperature near the surface of the deposited layer reaches a certain value, the two reach an equilibrium and the thickness of the wax layer does not change. In addition to the thickness of the wax layer, this critical temperature is also affected by the wax content of the deposited layer.

(3) After the deposit adheres to the pipe wall, it plays a role in heat insulation. On the one hand, the greater the thickness of the deposited layer, the better the heat insulation effect; on the other hand, the higher the wax content in the deposited layer, the greater the heat insulation effect and strength.

3.6. Effect of Wax Content on the Deposition of Gas−Liquid Two-Phase Flow.
Based on the 8% wax content of the initial oil sample, the two-phase gas−oil flow with a v_{sl} of 0.464 m·s^{-1} and a v_{sg} of 0.018 m·s^{-1} was studied, and the wax content was gradually increased to explore the effect of wax content on wax deposition. The test results show that for the bubbly flow, when the other conditions are constant, the thickness of the deposited layer increases as the wax content increases (Figure 9).

The reason is analyzed as follows: when the wax content increases, the WAT of the crude oil increases as well. In addition, the concentration gradient of the precipitated wax with respect to temperature will also increase. The diffusion of wax molecules becomes stronger, so the amount of wax deposits increases. The
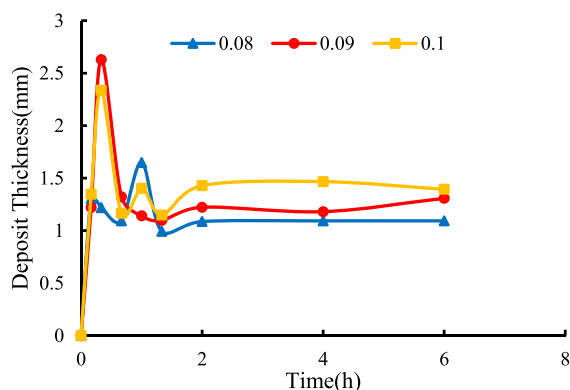
Figure 9. Wax deposition curves for different wax contents.

higher the wax content, the more likely wax crystals will precipitate when the WAT is reached.

4. CONCLUSIONS

(1) In the simulation of deep-sea low-temperature wax-deposition tests, the results show that the wax-deposition process of the pure liquid phase and gas−liquid two-phase flow can be described as follows: within a short period of time from the start of wax deposition, it rapidly accumulates to the peak, then rapidly cuts off part of it, and then presents a simple harmonic dynamic trend until the final stability.

(2) By completing the wellbore wax-deposition experiment with different v_{sl} and v_{sg}, the results show that when v_{sl} is constant, the thickness of the deposited layer decreases first and then increases with the increase of v_{sl}; when the v_{sl} is constant, as the v_{sl} increases, the thickness of the deposited layer first increases and then decreases.

(3) Wellbore wax-deposition tests with different oil-flow temperatures reflected that the thickness of the wax layer at the wall of the pipe decreased monotonously with the increase of oil temperature. When the test was carried out by changing the temperature of the water bath, the results reflected that when the pipe-wall temperature is low, the average wax-layer thickness of the two-phase gas−oil flow is basically unchanged and then decreases with the further increase of the pipe-wall temperature.

(4) The deposition tests with different wax contents reflected that the wax-layer thickness increased monotonously with the increase of wax content.

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■ REFERENCES

(1) Tinsley, J. F.; Prud'Homme, R. K. Deposition apparatus to study the effects of polymers and asphaltenes upon wax deposition. *J. Pet. Sci. Eng.* **2010**, *72*, 166−174.

(2) Duan, J.; Liu, H.; Guan, J.; Hua, W.; Jiao, G.; Gong, J. Wax deposition modeling of oil/gas stratified smooth pipe flow. *AIChE J.* **2016**, *62*, 2550−2562.

(3) Lei, Y.; Han, S.; Zhang, J. Effect of the dispersion degree of asphaltene on wax deposition in crude oil under static conditions. *Fuel Process. Technol.* **2016**, *146*, 20−28.

(4) Zhang, L.; Qu, S.; Wang, C. Prediction temperature field and wax deposition based on heat−fluid coupling method. *J. Pet. Explor. Prod. Technol.* **2018**, *9*, 639−644.

(5) Alade, O. S.; Hassan, A.; Mahmoud, M.; Al-Shehri, D.; Al-Majed, A. Novel Approach for Improving the Flow of Waxy Crude Oil Using Thermochemical Fluids: Experimental and Simulation Study. *ACS Omega* **2020**, *5*, 4313−4321.

(6) Elsharkawy, A. M.; Al-Sahhaf, T. A.; Fahim, M. A. Wax deposition from Middle East crudes. *Fuel* **2000**, *79*, 1047−1055.

(7) Halstensen, M.; Arvoh, B. K.; Amundsen, L.; Hoffmann, R. Online estimation of wax deposition thickness in single-phase sub-sea pipelines based on acoustic chemometrics: A feasibility study. *Fuel* **2013**, *105*, 718−727.

(8) Mansourpoor, M.; Azin, R.; Osfouri, S.; Izadpanah, A. A. Experimental investigation of wax deposition from waxy oil mixtures. *Appl. Petrochem. Res.* **2019**, *9*, 77−90.

(9) Joonaki, E.; Hassanpouryouzband, A.; Burgass, R.; Hase, A.; Tohidi, B. Effects of Waxes and the Related Chemicals on Asphaltene Aggregation and Deposition Phenomena: Experimental and Modeling Studies. *ACS Omega* **2020**, *5*, 7124−7134.

(10) Creek, J. L.; Lund, H. J.; Brill, J. P.; Volk, M. Wax Deposition in Single Phase Flow. *Fluid Phase Equilib.* **1999**, *158−160*, 801−811.

(11) Akinyemi, O. P.; Udonne, J. D.; Oyedeko, K. F. Study of effects of blend of plant seed oils on wax deposition tendencies of Nigerian waxy crude oil. *J. Pet. Sci. Eng.* **2018**, *161*, 551−558.

(12) Jinfang, Z.; Yuanzheng, J.; Yanqin, L. *A Wax Deposition Rate Model for Multiple Crude Oil. Control Conference*; IEEE, 2012.

(13) Khan, M. S.; Mukhtar, H.; Kait, C. F. *Study on Wax Deposition in Crude Oils*; National Postgraduate Conference (NPC). IEEE, 2011.

(14) Hamouda, A. A.; Ravneøy, J. M. *Prediction of Wax Deposition in Pipelines and Field Experience on the Influence of Wax on Drag-Reducer Performance: Offshore Technology Conference. Houston, Texas*; Offshore Technology Conference, 199212.

(15) Burger, E. D.; Perkins, T. K.; Striegler, J. H. Studies of Wax Deposition in the Trans Alaska Pipeline. *J. Pet. Technol.* **1981**, *33*, 1075−1086.

(16) Weingarten, J. S.; Euchner, J. A. Methods for predicting wax precipitation and deposition. *SPE Prod. Eng.* **1988**, *3*, 121−126.

(17) Hamouda, A. A.; Davidsen, S. *An Approach for Simulation of Paraffin Deposition in Pipelines as a Function of Flow Characteristics with a Reference to Teesside Oil Pipeline: SPE International Symposium on*

Oilfield Chemistry. San Antonio, Texas; Society of Petroleum Engineers, 199512.

(18) Hsu, J. J. C.; Brubaker, J. P. *Wax Deposition Measurement and Scale-Up Modeling for Waxy Live Crudes under Turbulent Flow Conditions: International Meeting on Petroleum Engineering. Beijing, China*; Society of Petroleum Engineers, 199510.

(19) Hsu, J. J. C.; Brubaker, J. P. *Wax Deposition Scale-Up Modeling for Waxy Crude Production Lines: Offshore Technology Conference. Houston, Texas*; Offshore Technology Conference, 199510.

(20) Elphingstone, G. M.; Greenhill, K. L.; Hsu, J. J. C. Modeling of Multiphase Wax Deposition. *J. Energy Resour. Technol.* **1999**, *121*, 81.

(21) Singh, P.; Fogler, H. S.; Nagarajan, N. Prediction of the wax content of the incipient wax-oil gel in a pipeline: An application of the controlled-stress rheometer. *J. Rheol.* **1999**, *43*, 1437−1459.

(22) Singh, P.; Venkatesan, R.; Fogler, H. S.; Nagarajan, N. Formation and aging of incipient thin film wax-oil gels. *AIChE J.* **2000**, *46*, 1059−1074.

(23) Singh, P.; Youyen, A.; Fogler, H. S. Existence of a critical carbon number in the aging of a wax-oil gel. *AIChE J.* **2001**, *47*, 2111−2124.

(24) Forsdyke, I. N. *Flow Assurance in Multiphase Environments: International Symposium on Oilfield Chemistry. Houston, Texas*; Society of Petroleum Engineers, 199710.

(25) Apte, M. S.; Matzain, A.; Zhang, H. Q. Investigation of Paraffin Deposition During Multiphase Flow in Pipelines and Wellbores—Part 2: Modeling. *J. Energy Resour. Technol.* **2001**, *123*, 150.

(26) Nilufer, K. *Multiphase Paraffin Deposition Behavior of a Garden Banks Condensate*; University of Tulsa: Tulsa, 2003.

(27) Yu, Z. *Study on Wax Deposition in Multiphase Flow*; China University of Petroleum: Beijing, 2012.

(28) Gong, J.; Zhang, Y.; Liao, L.; Duan, J.; Wang, P.; Zhou, J. Wax Deposition in the Oil/Gas Two-Phase Flow for a Horizontal Pipe. *Energy Fuels* **2011**, *25*, 1624−1632.

(29) Zheng, S.; Fogler, H. S.; Haji-Akbari, A. A Fundamental Wax Deposition Model for Water-in-Oil Dispersed Flows in Subsea Pipelines. *AIChE J.* **2017**, *63*, 4201−4213.

(30) Chi, Y.; Sarica, C.; Daraboina, N. Experimental investigation of two-phase gas-oil stratified flow wax deposition in pipeline. *Fuel* **2019**, *247*, 113−125.

(31) Zhihua, W.; Minglin, S.; Jinxiu, W. The Experimental Study on the Wax-Deposit Law in High-Pour-Point Crude Oil Transportation. *International Conference on Energy and Environment Technology (ICEET 2009)*; IEEE, 2009.