Systematic Study of Temperature and Different Types of Mixing in Paraffin Deposition Test Methods

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ABSTRACT: Paraffin fouling deposition is a common issue in oil production that leads to constrictions within the system wherever the system temperature drops below the wax appearance temperature (WAT). Chemical mitigation of these issues often relies on various laboratory equipment for product selection, but often the test conditions chosen are not representative of the field; therefore, the resulting deposit generated may give misleading results. In this article, our aim is to investigate how the use of different laboratory techniques can be utilized to generate a field-representative wax deposit. Our study includes the traditional cold finger (CF) apparatus, the coaxial shear cold finger (CSCF), and the dynamic paraffin deposition cell (DPDC), a test method developed in house. The pieces of equipment use similar temperature-driven deposit formation to measure fouling but with very different mixing conditions. The study of paraffin deposition at narrow temperature gradients with these techniques showed similar trends for deposit weight when compared to the fouling factor resulting deposit generated may give misleading results. In this article, our aim is to investigate how the use of different laboratory techniques can be utilized to generate a field-representative wax deposit. Our study includes the traditional cold finger (CF) apparatus, the coaxial shear cold finger (CSCF), and the dynamic paraffin deposition cell (DPDC), a test method developed in house. The pieces of equipment use similar temperature-driven deposit formation to measure fouling but with very different mixing conditions. The study of paraffin deposition at narrow temperature gradients with these techniques showed similar trends for deposit weight when compared to the fouling factor.

1. INTRODUCTION

Paraffin wax is considered to be acyclic saturated hydrocarbons or n-alkanes present in crude oil as a mixture with a broad distribution in carbon number and, when above n-C_{150}, can cause problems in the flow assurance area. These paraffins will crystallize and drop out of the liquid oil phase below a certain temperature known as the wax appearance temperature (WAT). As the production fluids are pumped through a flowline, the temperature can decrease to somewhere between ambient and the temperature of the production fluid, causing a temperature gradient in the pipeline or due to the Joule Thomson effect. Wax deposition in oil-field production can cause fouling and plugging issues and may cause further damage to installed equipment, leading to production upsets and loss. Oil producers can employ thermal, mechanical, or chemical methods to prevent or remediate wax deposition. For chemical selection, laboratory test methods are used to develop products appropriate for those applications; therefore, there is the necessity of understanding how different paraffin deposition test methods can best generate the most field-like paraffinic deposits.

The most used test methods are cold fingers and flow loops. A cold finger* consists of a refrigerated surface that is inserted into a jar containing a heated crude oil. The temperature gradient formed on the surface promotes the wax deposition, and after a determined period of time, the surface is removed from the fluid and the deposit is weighed. A flow loop is a closed system of fluid flow in pipes or tubing with a refrigerated measuring section that usually can be removed to analyze the deposit that is formed. The second test method is aimed to be the most representative of field conditions due to flow regime similarities and thus shear stress, which impacts the formation of wax deposit. Using both test methods, for example, Bern et al. evaluated the temperature and shear effect on paraffin deposits and concluded that there are two...
mechanisms affecting deposition: molecular diffusion, which transports the paraffin-wax molecules that are in solution, and shear dispersion, which transports the already crystallized wax. Singh, using a flow loop, proposed a more complex wax deposition mechanism but, similarly to Bern, also observed that molecular diffusion is the predominant mechanism for wax deposition as well as the deposition phenomena being a strong function of the temperature difference across the deposit. On the other hand, shear is seen as important only when there is a high concentration of crystallized wax in the bulk oil, which is relevant only at temperatures significantly below the WAT. Other authors also using flow loops, show the impact on deposit mass and n-alkane distribution when working with temperatures below the WAT as well as using different temperature gradients.

Similar observations have been reported by others using a cold finger apparatus instead of a flow loop, where the importance of temperature selection on the carbon chain distribution, shear increase, and molecular diffusion was investigated. Other authors have also claimed to obtain similar laboratory deposited n-alkane distributions to the field by adjusting the test conditions with the purpose of evaluating paraffin inhibitors.

As discussed previously, a different apparatus, such as the flow loop, has been used to evaluate the paraffin deposition in order to better represent the field conditions in terms of temperature distribution and shear regime; however, there are significant limitations to such test methods, including sample volume and test duration. These limitations make the tests relatively impractical for rapid chemical control product performance screening; therefore, the need for a test method with smaller oil volumes and a shorter test duration is necessary. Historically, the industry has utilized the cold finger apparatus (previously described) to evaluate paraffin deposition in the laboratory for product recommendation; however, different design iterations of this equipment have been proposed throughout the industry over time in an attempt to better reproduce the shear conditions seen in the field. These changes are usually related to the different forms of crude oil sample agitation during the deposit formation over the test period. Some of these apparatuses can promote mixing by using a stir bar, rotating the test cell external wall, using a blade disc turbine, or rotating the refrigerated surface (finger) itself. In this work, we present a comparison of three distinct sets of paraffin deposition equipment in order to evaluate the importance of temperature conditions and different mixing mechanisms on the composition of the deposits formed in the laboratory and how the composition compares to the actual field deposit. This first piece of equipment is the most commonly used cold finger setup, which we call a “traditional” cold finger, in which the refrigerated surface is inserted vertically inside the sample and the homogenization is promoted exclusively with the use of a stir bar at the bottom of the test cell containing the crude oil. The second technique utilizes an apparatus developed in house, the dynamic paraffin deposition cell (DPDC), and proposes a different orientation in which the test cell is kept horizontally inside a shaker bath as well as the internal refrigerated surface and the homogenization is due to the horizontal movement of the complete cell throughout the test. The initial purpose of this design is to perform paraffin deposition tests in the presence of brine, where the horizontal agitation maintains a more homogeneous fluid throughout the test, promoting the contact of both phases with the refrigerated surface. The third paraffin deposition apparatus used here is the coaxial shear cold finger (CSCF), based on the design of Lima, to better represent the field shear conditions. The sample homogenization in this equipment is aided by the rotation of the refrigerated finger itself, resulting in a different mixing regime when compared to that of the other two pieces of equipment. As a further understanding of the tests available, it was also evaluated how the different deposition tests correlate with the Para-window technique that differs in the method of paraffin deposition measurement, while the previous tests used gravimetry, the Para-window measures the fouling potential of the crude oil using a laser probe, which reads the transmitted light between the probe and the mirrored surface throughout the test without removing the refrigerated surface from the bulk oil.

The purpose of this study is to shed some light on the different test methods available in our laboratories, and in a future study, examine how it affects the paraffin control product performance and thus product selection. The goal of using different test methods is to use a systematic approach to understand the impacts of temperature and mixing when using test methods with different agitation mechanisms and thus flow patterns. The impact of these variables is evaluated mainly by analyzing the n-alkane distribution profile of the deposits generated by each test method for two different crude oils and how closely they correlate to their respective field deposits.

2. RESULTS AND DISCUSSION

Our previous work showed that the optimal test conditions for obtaining a deposit in the laboratory with an n-alkane distribution similar to that in the field is the one that utilizes a small temperature gradient, 5 °C, that is close to the WAT. A similar study is described below that evaluates if the different mixing mechanisms (Figure 1) associated with the three unique paraffin deposition units would have any impact on the conclusions drawn from the previous publication introducing the Para-window. The first part of the discussion examines the temperature effect on n-alkane distribution across the three units, while the second part investigates the effect of varying the shear stress using the CSCF apparatus.

2.1. Temperature Study. Two different sets of crude oils (Table 1) and their respective field deposits collected on the same system were used for this study. The laboratory-generated deposits were obtained using two temperature conditions, one using a small temperature gradient (5 °C) between the refrigerated surface and bulk oil and the other...
For the second condition, $T_{30,40}$°C refrigerated surface (the three distinct pieces of equipment to generate the para-deposit (Figure 2) compared to the Para-window fouling.

Table 1. Crude Oil Samples Used for This Study

| sample | provenance | WAT (°C) | °API | % $n$-paraffins $\geq n$-$C_{35}$ | dynamic viscosity (mPa·s$^{-1}$) |
|--------|------------|----------|------|---------------------------------|--------------------------------|
| A      | Niobrara   | 38       | 35   | 7.6                             | 4.83@ 40 °C                    |
| B      | Permian    | 32       | 41   | 5.8                             | 3.00@ 35 °C                    |

$^*$As determined by HTG.

using a large temperature gradient (25 °C for crude A and 20 °C for crude B). For the first condition, the bulk fluid temperature ($T_{\text{bulk}}$) was kept right above the WAT, and the refrigerated surface ($T_{\text{surface}}$) was cooled to 5 °C below $T_{\text{bulk}}$. For example, crude A test temperatures were 40–35, 35–30, 30–25, 25–20, and 20–15 °C, and for crude B, the temperatures were 35–30, 30–25, 25–20, and 20–15 °C. For the second condition, $T_{\text{bulk}}$ was right at the WAT and $T_{\text{surface}}$ was 25 to 20 °C below the $T_{\text{bulk}}$ temperature ($\Delta T = 25$ °C for crude A and 20 °C for crude B) (i.e., for crude A, $T_{\text{bulk}} = 40$ °C and $T_{\text{surface}}$ at 15 °C, while for crude B, $T_{\text{bulk}} = 35$ °C and $T_{\text{surface}}$ at 15 °C). The second temperature condition is the one commonly used to perform tests with the traditional cold finger technique.

The initial analysis investigated the deposit weights obtained under the different temperature conditions noted above using the three distinct pieces of equipment to generate the paraffin deposit (Figure 2) compared to the Para-window fouling.

![Figure 2](image-url)  
**Figure 2.** Deposit weight obtained and error bars representing the standard error value of the measurements with the three deposition units (traditional CF, CSCF, and DPDC) for (A) crude A and (B) crude B using a $\Delta T$ of 5 °C compared to the fouling profile obtained using the Para-window at the same surface temperatures and temperature gradient.

It was observed that the deposit weights generated from both crudes using each of the three methods follow the same trend as indicated by the fouling profile obtained with the Para-window equipment (i.e., as the fouling factor increases or decreases, the deposit weight obtained using each deposition unit ($\Delta T = 5$ °C) will also increase or decrease in a general manner, as can be seen in Figure 2). This correlation is most pronounced for the traditional cold finger, which is believed to be due to the low agitation conditions since only a magnetic stir bar is utilized for mixing in both pieces of equipment. Although the same fouling trend is observed when using the deposition units, the amount of deposit generated using the small temperature gradient and close to the WAT is low for all three pieces of equipment, reinforcing the importance of having a sensitive test method that is capable of detecting and measuring the initial discrete fouling event involving the most insoluble wax, such as the Para-window.

A similar approach used in our previous study was applied here, focusing on the deposit n-alkane distribution using the n-alkane peak ratios of the chromatograms obtained by high-temperature gas chromatography (HTGC) analysis. As in the previous study, the non-n-alkane components were not included in the evaluation. Figure 3 shows the chromatogram of the deposits obtained using the three different pieces of equipment under the condition of $T_{\text{bulk}}$ at 40 °C and $T_{\text{surface}}$ at 35 °C for crude A (Figure 3A) and $T_{\text{bulk}}$ at 30 °C and $T_{\text{surface}}$ at 25 °C for crude B (the temperature at which it was possible to recover a deposit for this crude with every apparatus) as compared to the respective field deposits. Not only is a similar carbon distribution observed for all the three pieces of equipment when looking at the long-chained n-alkane region ($\geq n$-$C_{35}$) of the chromatogram, but the carbon distributions are also very similar to that of the field deposit. When expanding the analysis to other temperatures using the HTGC data, the ratio among four different peaks in the high-molecular-weight region ($\geq n$-$C_{35}$) was used to facilitate the comparison: for crude A ($n$-$C_{35} + n$-$C_{36})/(n$-$C_{45} + n$-$C_{46}$) and for crude B ($n$-$C_{41} + n$-$C_{55})/(n$-$C_{47} + n$-$C_{48}$). These peaks were selected for this study on the basis of the peaks that would best represent the shift of the carbon chain distribution from the higher to the lower molecular weight. Small values of peak ratios indicate that the laboratory-generated deposit has a distribution more similar to the one observed in the field deposit. Figure 4 shows that when using a $\Delta T$ of 5 °C, as the test temperature moves away from the WAT, the peak ratio becomes higher, indicating that the carbon distribution of the laboratory-generated deposits shifts away from the one observed for the field deposit. The same behavior is observed when using a large $\Delta T$ (Figure 4A,B), which leads to a deposit more enriched in low-molecular-weight paraffins ($\leq n$-$C_{35}$) rather than the long-chained ones present in the field deposit. These results indicate that although the three different apparatuses present different homogenization mechanisms, the carbon chain distribution is mainly driven by temperature, and a small gradient close to the WAT will give an n-alkane distribution similar to the field deposit at the high molecular weight ($\geq n$-$C_{35}$) portion, confirming the results of the previous study. It is worth noting that looking at the complete n-alkane distribution, that includes the low-molecular-weight wax portion ($\leq n$-$C_{35}$) in Figure 5, there is a slight shift in the carbon chain distribution for crude A among the methods and it is less pronounced in crude B. For crude A, the traditional cold finger and DPDC results present a maximum distribution...
at \( n-C_{15} \) to \( n-C_{16} \) whereas the CSCF presents a maximum at \( n-C_{20} \) to \( n-C_{21} \). These differences may be caused by the different flow patterns present in the units, but when compared to the field deposits, the short-chained \( n \)-alkanes (\( \leq n-C_{35} \)) are not present, which is likely due to aging of the deposit in the field.

**2.2. Shear Study.** For the second part of this study, the CSCF equipment was used to investigate the effect of increasing shear stress on both the deposit weight and \( n \)-alkane distribution. This evaluation was performed only with this equipment due to the possibility to roughly estimate the shear stress values on the rotating finger surface as described in the Experimental Section. For this set of experiments, the same temperature conditions as described in the previous section, using the small and large temperature gradients but different rotational speeds of the refrigerated fingers, are used. These two gradients were used to verify if the shear effect would have a higher impact on the large temperature gradient than in a small temperature gradient.

The deposit weight data presented in Figure 6 shows a significant reduction in deposit weight as the rotation increases from 300 to 930 rpm, mainly when the large temperature gradient is used. The same effect was reported previously by other authors\(^5,13\) that when increasing the shear stress of the system, a reduction in deposit mass was observed. A more in-depth analysis of the deposits looking at the \( n \)-alkane distribution is shown in Figures 7 and 8. The deposits were obtained under the same temperature conditions, \( 40-35 \) °C for 24 h but at low (\( \sim 0.5 \) Pa) and high shear (\( \sim 3 \) Pa) for crude oil A and \( 35-30 \) °C for 24 h at low (\( \sim 0.5 \) Pa) and high shear (\( \sim 3.5 \) Pa) for crude oil B. As can be seen, the results in the chromatograms show a similar \( n \)-alkane distribution in the long-chain \( n \)-alkane region under both shear conditions. In Figure 8, a peak ratio analysis, \( (n-C_{35} + n-C_{36})/(n-C_{45} + n-C_{46}) \) for crude A and \( (n-C_{41} + n-C_{55})/(n-C_{47} + n-C_{48}) \) for crude B, shows that as the small temperature gradient is shifted away from the WAT (\( 35-30, 30-25, 25-20, \) and \( 20-15 \) °C), the peak ratio is slightly reduced at the higher shear rate; however, the deposits generated using these temperature ranges are still not field-like overall (indicated by a higher peak ratio). When looking at the optimal temperature range of \( 40-35 \) °C, where the peak ratios are minimized, the increased shear has little

Figure 3. HTGC of crude deposits generated from different apparatuses (traditional cold finger, DPDC, CSCF) with bulk oil temperature, \( T_{\text{bulk}} \) at \( 40 \) °C and a cold temperature of \( 35 \) °C compared to field deposit for crude A (A) and \( T_{\text{bulk}} \) at \( 30 \) °C and a cold temperature of \( 25 \) °C for crude B (B). Deposits from DPDC equipment at temperatures of \( 35-30 \) °C were not enough to recover for HTGC analysis; therefore, the comparison here is between \( 30 \) and \( 25 \) °C to show the similarities in the chain distribution among different pieces of equipment.

Figure 4. (A) \( n \)-Alkane HTGC response ratio \( (n-C_{35} + n-C_{36})/(n-C_{45} + n-C_{46}) \) depicting paraffin distributions from various test temperature windows compared to the field deposit (0.03) for crude oil A. (B) HTGC response ratio \( (n-C_{41} + n-C_{55})/(n-C_{47} + n-C_{48}) \) of laboratory-generated deposits at different temperatures compared to the field deposit (0.25) for crude oil B.
effect on the carbon distribution in the high-molecular-weight region, reinforcing the idea that the temperature is the main driver to obtaining a deposit with a composition similar to that of the field. However, an analysis of the complete chromatogram at the same temperature (Figure 7) shows that the deposit generated at high shear does have a higher proportion of lower-molecular-weight n-alkanes as compared to the deposit generated at low shear. Peaks of the complete chromatogram (Figure 8), different from the ones used previously, were selected to show the slight shift in the peak ratio of the lower-molecular-weight to higher-molecular-weight n-alkanes. Looking at the following peaks for crude A (n-C46 + n-C47)/(n-C18 + n-C19), the ratio changes from 3.6 at low shear to 1.3 at high shear and is less pronounced for crude B, where the peak ratio (n-C49 + n-C50)/(n-C16 + n-C17) changes from 0.6 to 0.5 from low to high shear. Although these are only small shifts, the results were unexpected considering that previous studies have shown that increasing shear will promote the enrichment of paraffins of high molecular weight due to the removal of entrained oil and/or low-molecular-weight paraffins that would be expected to occur with greater mixing/shear. In this case, however, the difference could be attributed to the fact that at high shear the higher-molecular-weight paraffins are deposited on the walls of the cell due to greater centrifugal forces associated with higher shear mixing and therefore appear to be relatively reduced in the overall chromatogram compared to the lower-shear chromatogram. The hypothesis is supported by the fact that at the end of the test, small but noticeable amounts of paraffin were observed on the wall of the cell near the oil–air interface following the high-shear but not the low-shear experiments.

Overall, changing the shear stress, at laboratory scale values, does not seem to have a significant effect on the carbon chain distribution. However, temperature is still the main factor in generating more field-like laboratory deposits. Furthermore, in this set of experiments, the increased shear possibly induced a centrifugal effect that, contrary to what others have observed, reduced the ratio of long- to short-chained n-alkane paraffins.

3. CONCLUSIONS

A systematic study has been conducted using three distinct paraffin deposition apparatuses containing a cold finger as the refrigerated surface and different mechanisms of sample mixing...
or homogenization. The findings show that the deposits generated using the different test methods were very similar in composition despite the different amounts of mixing/shear present during the experiments. The main factor in generating a laboratory deposit with an n-alkane distribution similar to the field regardless of the test method used is the careful selection of temperatures for the experiment, which includes the utilization of a small temperature gradient (5 °C) that is close to the WAT. For example, for crude A with a WAT of 38 °C, the temperatures needed to run the deposition tests would ideally be 40–35 °C, and for crude B with a WAT of 32 °C, the temperature would be 35–30 °C. The findings indicate that the paraffin deposition mechanism is mainly driven by temperature and that different mixing has some impact on the low-molecular-weight n-alkane region of the carbon chain distribution (≤n-C_{35}).

Upon further investigation of the effect of shear stress changes on the generation of a deposit using the CSCF, at same temperature, a reduction in the deposit weight was observed with higher shear, as previously reported in the literature, but the carbon distribution was not impacted significantly when working at temperatures close to the WAT and using a small temperature gradient (5 °C). The results again confirm that temperature is the main driver dictating the nature of the most field-representative deposit characteristics using the laboratory test systems available. This presents the opportunity to gain better insights into paraffin deposition in the laboratory using the present equipment and prepares us to develop better screening capabilities in order to meet current and future paraffin challenges faced in the field.

4. EXPERIMENTAL SECTION

For this study, two oil samples were used from two different petroleum systems, Niobrara (crude A) and Permian (crude B), and their API, WAT, % n-paraffin content (summation of n-C_{16} to n-C_{68}), and dynamic viscosity are recorded in Table 1. Field deposits were collected from the well tubing of the parent crude (i.e., field deposit A was from crude A and field deposit B was from crude B). The crude oils were used to generate the

Figure 7. Complete chromatograms of deposits generated using CSCF at low and high shear compared to the field deposit and crude oil. (A) Deposits obtained with crude oil A at T_{bulk} = 40 °C and T_{surface} = 35 °C. (B) Deposits obtained with crude oil B at T_{bulk} = 35 °C and T_{surface} = 30 °C.
4.2. Wax Appearance Temperature (WAT). WAT is the temperature at which the paraffin molecules start to crystallize. The WAT of the crude oils was determined using a TA Instruments DSC Q20. The sample was previously heated at 60 °C, and approximately 5 mg of crude was poured into the test pan. The pan was placed in the DSC equipment, and the WAT was obtained using the following method: equilibrate the sample at 70 °C to erase the thermal history and cool the sample at a rate of 2 °C/min to observe any heat flow variation related to crystallization within the range of 70 to −20 °C.

4.3. High-Temperature Gas Chromatography (HTGC). The high-temperature gas chromatography analyses of the crude oils, laboratory deposits and field deposits were all performed at a third-party laboratory, and a summarized description is presented here. The equipment used was an Agilent 6890N gas chromatograph (GC) with an Agilent DB-1 column using a constant pressure of helium as the carrier gas and a temperature at the injector of 275 °C. The column oven was programmed to hold at 30 °C for 5 min and then was set to increase to 320 °C at 3 °C min⁻¹, at which point it was held for 20 min. Components eluting from the column were detected by a flame ionization detector (FID) held at 350 °C. Under these chromatographic conditions, n-alkanes, key isoprenoids, key aromatic compounds, and the lighter hydrocarbons are detected. Crude oil standards are run periodically to check retention times and other chromatographic performance criteria. Further details can be seen in a previous work.15

4.4. Temperature-Controlled Reflectance Cell, Para-window. The temperature-controlled reflectance cell, Para-window, can be seen in detail in Russell et al.15 The crude oil is first heated to 60 °C and then poured into the glass test cell (400 mL) with a stir bar. The mirrored surface temperature (T_surface) is set initially to the same temperature as the crude oil (T_bulk). Once the crude oil and mirror are at the same temperature, the head assembly containing the mirror is attached to the double-walled glass bottle, and data recording of the bulk oil temperature, mirror temperature, and NIR light transmittance is initiated. After obtaining a baseline (5 min), the temperature of the mirror is lowered to the predetermined target and left to soak for 1 h. The fouling tendency recorded during a single test is determined by transforming the raw light transmittance to optical density and then comparing the standard deviation over the whole curve generated during the temperature soak time. The standard deviation is multiplied by 10 000 and termed the fouling factor. Optical density is calculated from eq 1, where TRANS represents transmittance at a given time during the test.

\[
\text{optical density} = -\log \left( \frac{\text{TRANS}}{100} \right)
\]

4.5. Paraffin Deposition Apparatus. The paraffin deposition equipment, cold finger, is commonly used throughout the industry to evaluate paraffin inhibitor performance. It consists of a bath or heating block which keeps the crude at a constant temperature (T_bulk) and a metal surface immersed in the bulk oil with a cold fluid circulating within it to keep the temperature below the bulk oil temperature (T_surface). The temperature gradient between the surface and the bulk oil sample induces the wax deposition.

Three different apparatuses with the same operating principle of a cold finger as far as wax deposit measurement are used in this study. Although the general measurement of laboratory paraffinic deposits with the traditional CF, DPDC, and CSCF to be compared to the corresponding field deposit. Both types of deposit were evaluated by high-temperature gas chromatography, HTGC, in order to obtain their n-alkane distribution.

The fouling profile was also obtained for both crude oils using the Para-window technique in order to be compared to the deposit weights generated with the laboratory deposition techniques.

The test methods used are briefly described here, and more details can be found in our previous paper.15

4.1. Crude Oil Sample Conditioning. Before any of the tests were performed, the crude oil was heated to a temperature of at least 15 °C above the WAT in order to melt any paraffin crystal present in the sample. This facilitates the standard homogenization of the crude oil, and as demonstrated by Oliveira et al., the temperature that the crude oil is heated prior to testing can impact some properties directly related to the paraffins, such as the pour point and yield stress. For this reason, the two crudes used here are heated to the same temperature of 60 °C, mixed, and subsampled in the test cell of the different pieces of equipment.

![Figure 8.](https://dx.doi.org/10.1021/acsomega.0c01069)
deposition is similar, the different setups are distinct for the sample agitation mechanism throughout the deposition test. All three deposition test methods are described below and use between 100 and 150 mL of crude oil per test cell, with similar refrigerated surface dimensions differing mainly over the contact area with the fluid due to the vertical and horizontal surface arrangement. A scheme representing the different agitation mechanisms can be seen in Figure 1. The tests for all of the different deposition apparatuses were performed for 24 h at the following $T_{\text{bulk}} - T_{\text{surface}}$ temperatures: 40–35, 35–30, 30–25, 25–20, 20–15, and 40–15 °C for crude A and 35–30, 30–25, 25–20, 20–15, and 35–15 °C for crude B.

4.6. Traditional Cold Finger (CF). In the traditional cold finger apparatus, the heated oil sample is poured into glass test cells (100 mL), and these are placed in the cold finger temperature-controlled water bath at the desired temperature of the bulk fluid ($T_{\text{bulk}}$). A stir bar is added to the cells in order to promote the sample homogenization during the test and for this study a rotation of 350 rpm was used. The chiller lines are connected to the deposition surface (cold finger) at the desired temperature ($T_{\text{surface}}$), which for this study can be 5 °C or more below the temperature of the bulk ($T_{\text{bulk}}$). Once assembled, the test runs for 24 h, and at the end of the test, the fingers are removed and left to dry. The remaining material is then weighed and collected for HTGC analysis.

4.7. Coaxial Shear Cold Finger (CSCF). A coaxial shear cold finger from PSL Technik presents an operating mechanism similar to the traditional cold finger, in which a cold surface (cold finger) is inserted vertically into the heated cell containing crude in order to observe the deposits formed on the cold surface. The equipment cell dimensions were based on the equipment described by Lima.$^{13}$ The glass bottles containing 150 mL of crude oil are attached to the fingers at the outer part of the apparatus, and the fingers are then rotated. The upper part of the equipment containing the cells with the crude oil is lowered into the water bath at the desired temperature ($T_{\text{bulk}}$). After 24 h, the bottle is slowly removed, and the finger sleeve containing the deposit is removed and weighed and the deposit is recovered for HTGC analysis. The tests were performed with different temperatures and temperature gradients depending on the crude oil and test conditions.

This equipment was also used to evaluate the effect of increased mixing, or shear, on the $n$-alkane distribution. Two different finger rotations were selected, 300 and 930 rpm, for both crudes. The Reynolds number for the CSCF was calculated using eq 2 for Couette–Taylor$^{17}$ systems

$$Re = \frac{r_i \omega (r_e - r_i) \rho}{\mu}$$

where

- $Re$ = Reynolds number,
- $\omega$ = angular velocity,
- $r_i$ = radius of internal cylinder (rotating finger),
- $r_e$ = radius of external cylinder (flask bottle),
- $\rho$ = fluid density, and
- $\mu$ = fluid dynamic viscosity at $T_{\text{bulk}}$.

The Reynolds numbers were calculated at the two different rotations using the fluid viscosity at $T_{\text{bulk}}$ right above the WAT (40 °C for crude A and 35 °C for crude B). The Reynolds number for crude A varies from 1000 to 3000 between the tests performed at rotations of 300 and 930 rpm, and crude B present larger Reynolds numbers from 1580 to 4900 for the same rotational values.

Considering the complex flow patterns generated at the finger surface, ideally a computer simulation similar to the one performed by Lima$^{13}$ should be performed to estimate the shear stress on the finger wall. However, for this study a simplified calculation of the shear stress ($\tau_{\text{cyl}}$) was conducted using eq 3,$^{11}$ which gives underestimated values of shear stress in the range of 0.5 Pa for both crudes at the lowest rotational speed and at about 3.0–3.5 Pa at the highest rotational speed. These shear stress values are lower than the ones usually observed in the field but are distinct enough for the present study.

$$\tau_{\text{cyl}} = 0.0791 \rho \omega^3 \tau_{\text{cyl}}^2$$

where

- $\tau_{\text{cyl}}$ = shear stress on the finger surface,
- $\rho$ = fluid density,
- $Re$ = Reynolds number,
- $\omega$ = angular velocity, and
- $r_{\text{cyl}}$ = radius of the cylinder (finger).

4.8. Dynamic Paraffin Deposition Cell (DPDC). About 100 mL of conditioned crude oil is loaded into the test cells, and the surface to be refrigerated is immersed in the crude oil. The test cells are placed horizontally inside a shaker bath where the water bath maintains the bulk oil temperature ($T_{\text{bulk}}$). The chiller lines at $T_{\text{surface}}$ are connected to the cells to refrigerate the deposition surface, the shake rate of the bath is adjusted to the desired value of about 100 spm (strokes per minute), and the test is run for 24 h. Horizontal shaking creates the mixing condition inside the cells. The specific temperatures and temperature gradients are indicated for the results.

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### Notes

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