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Development of an Approach for Determining the Effectiveness of Inhibition of Paraffin Deposition on the Wax Flow Loop Laboratory Installation

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Abstract: The formation of wax deposits is a common phenomenon in the production and transportation of formation fluids. On the territory of the Perm Krai, this problem occurs in half of the mining funds. One of the most common and promising methods of dealing with these deposits is the use of inhibitor regents. The most popular technique for assessing the effectiveness of a wax inhibitor is the «Cold Finger», which has a number of significant drawbacks. This work presents a number of methods for assessing the effectiveness of inhibition of paraffin formation on the laboratory installation «WaxFlowLoop». A number of laboratory studies have been carried out to determine the effectiveness of a paraffin deposition inhibitor for inhibiting the paraffin formation process of four target fluids. Verification of the obtained values was carried out by comparing them with the field data. As a result of laboratory studies, it was found that the value of the inhibitor efficiency, determined by the «Cold Finger» method, differs from the field data by an average of 2 times. At the same time, the average deviation of the results determined at the «WaxFlowLoop» installation from the field data is 8.1%. The correct selection of a paraffin deposition inhibitor and its dosage can significantly increase the inter-treatment period of the well, thereby reducing its maintenance costs and increasing the efficiency of well operation.

Keywords: wax deposits; laboratory studies; inhibitors; effectiveness; complication

Citation: Ilushin, P.; Vyatkin, K.; Kozlov, A. Development of an Approach for Determining the Effectiveness of Inhibition of Paraffin Deposition on the Wax Flow Loop Laboratory Installation. *Inventions* **2022**, *7*, 3. https://doi.org/10.3390/inventions7010003

Academic Editor: Alexander Klimenko

Received: 20 October 2021
Accepted: 10 December 2021
Published: 21 December 2021

1. Introduction

On the territory of Russia, about 25% of oil deposits are characterized by the maximum saturation of reservoir oils with paraffinic hydrocarbons and high pour points of degassed oils [1,2]. The formation of wax deposits (wax deposition) on the inner surface of the production tubing is one of the most common complications in oil production [3,4]. The formation of these deposits leads to an increase in the pressure in the production tubing, an increase in the load on oilfield equipment, and the occurrence of accidents [5,6]. The problem of the formation of these deposits is relevant both for many fields around the world and for the fields of the Perm Krai (Figure 1) [7–10].

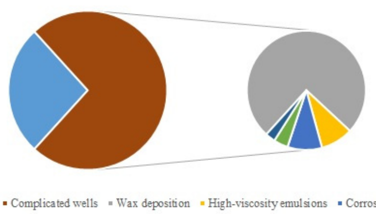

Figure 1. Composition of operational and complicated funds of the Perm Krai.

Modern oil production is characterized by a high rate of digitalization of the processes of oil production and transportation [11,12]. At the same time, the modeling of wax formation processes plays an important role in the modeling of many technological processes in the fields. A number of methods have been developed for assessing the probability of adhesion of these deposits, as well as the spatial-temporal distribution of the formed deposits ("RRR" model, Matzain model and Heat analogy) [13–15]. The use of these techniques makes it possible to assess the need to combat organic sediments, to choose more effective methods of control and the parameters of their application [16].

The fight against these complications occurs in two ways: prevention of the formation and removal of formed deposits. Methods of preventing the formation of wax deposits are considered the most promising [17]. The use of these methods is considered preferable, since the prevention of the occurrence of wax deposits on oilfield equipment reduces the risk of accidents and allows for the preservation of valuable components in the oil—high-molecular compounds that are used to obtain petrochemical products [18]. The most common and effective method in this group is the use of chemical reagents—inhibitors of the formation of wax deposition. The principle of their action is based on various adsorption processes, depending on which they are divided into groups: wetting agents, dispersants, modifiers, depressants, and reagents of complex action [19–21]. A wide range of substances are used as additives: alkyl aromatic compounds, esters, nitrogen-containing compounds, polymer type substances [22–24]. The main principle of action of these reagents is to reduce the temperature of oil saturation with paraffins and prevent the formation of solid deposits [25,26].

Determination of the technological efficiency of the reagent-inhibitor for the target fluid is often performed in laboratory conditions. The most common technique for assessing technological efficiency is the «Cold Finger» [27–29]. This installation includes special containers for fluid, «cold» rods, the inner surface of which is cooled using a circulation thermostat and a pump to create a significant temperature gradient. The operation of this laboratory installation is based on the principle of the reversed pipeline (Figure 2) [30]. Inside the «cold rods» there is a cavity, at the bottom of which coolant flows. The «cold rod» is lowered into a special flask with the investigated fluid heated to the required temperature. At the bottom of flask is a magnetic stirring device.

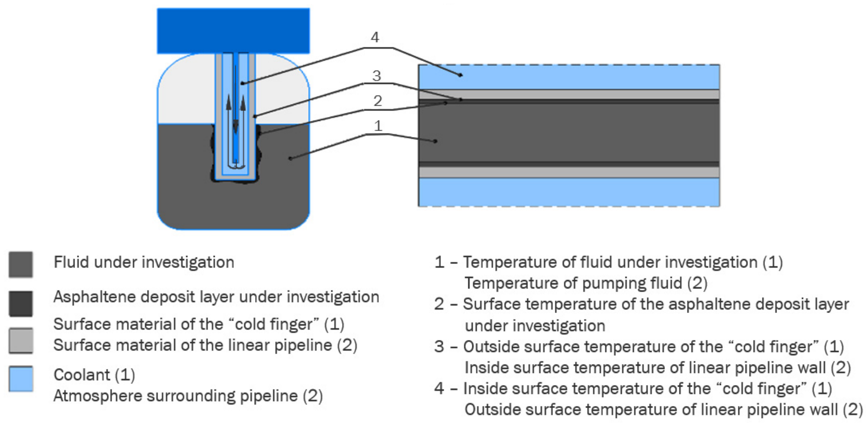

Figure 2. The principle of the reversed pipeline, implemented in the laboratory installation «Cold Finger».

Due to the creation of a temperature gradient between the investigated fluid and the surface of the «cold rod», wax deposits begin to settle on it. The most obvious disadvantage of this method is the impossibility of reproducing the thermobaric and kinematic conditions for the formation of wax deposits. The studies carried out on this laboratory installation often differ significantly from the real field data, which is a consequence of its shortcomings indicated earlier [31].

The purpose of this study is to develop a methodology for evaluating the effectiveness of the use of wax deposition inhibitors at the modern «WaxFlowLoop» installation, assessing the correlation of the obtained values with laboratory studies at the «Cold Finger» installation and with field data.

2. Materials and Methods

Laboratory studies on the CF-4 «Cold Finger» installation were carried out for 2 h. The temperature in the water bath was 45 °C, and the temperature on the surface of the «Cold Finger» was 5 °C. Stirring of the studied oil sample was carried out using a magnetic stirring device, and the speed was from 0 to 700 rpm [32,33]. Laboratory studies were carried out simultaneously on four «cold» rods, and the final value was determined as the average value. The averaging of the measured parameters made it possible to avoid distortion of the research results, due to the presence of the errors in this method for determining the intensity of the formation of wax deposits. The intensity of the formation of wax deposits was determined by Equation (1), and the efficiency of using the considered reagents-inhibitors was determined by Equation (2) [34].

$$I = \frac{m_{dep}}{m_{oil}} \cdot 100\% \tag{1}$$

$$E = \frac{(I_h - I_i)}{I_h} \cdot 100\% \tag{2}$$

where m_{dep}—mass of the formed deposits, g; m_{oil}—mass of the investigated oil sample, g; I_h—intensity of wax formation without inhibitor dosage, %; I_i—intensity of wax formation during inhibitor dosage, %.

Currently, there are modern methods for studying the kinetics of wax deposits formation, including assessing the effectiveness of wax deposition inhibitors. These methods include the laboratory installation «WaxFlowLoop» (Figure 3) [35–37]. This installation includes: a pump (b), a differential pressure gauge (h), a test section (c) cooled through an external pipeline (d), a feed tank (a) with an external liquid-cooled (j), liquid level sensor (i), and Coriolis flowmeter (f). The diagram also shows the directions of movement of the coolant and the fluid under study.

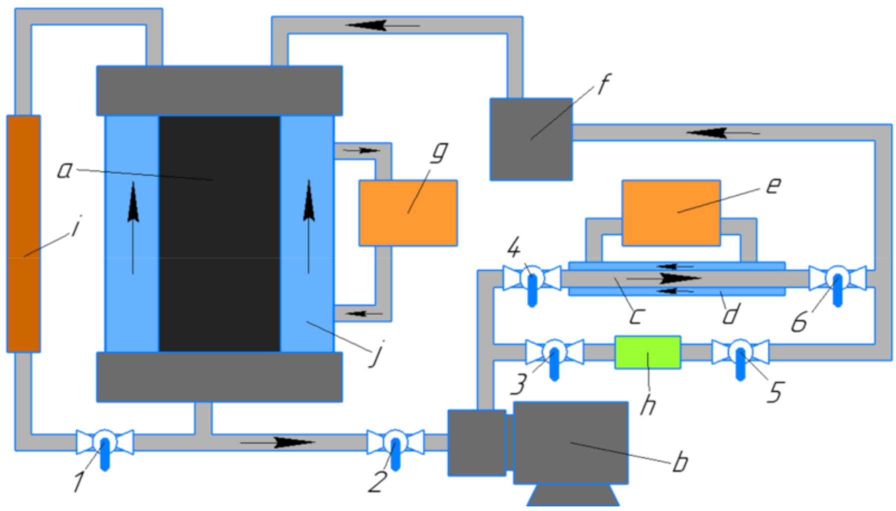

Figure 3. Hydraulic diagram of the laboratory installation «WaxFlowLoop».

The algorithm of work on this installation begins with filling the raw tank with the oil under investigation and checking the liquid level in it (valves 5 and 1). Then, on the thermostats (g and e), connected to the outer cylinder of the raw tank (a) and the test section (c), a temperature is set that exceeds the temperature of the onset of paraffin crystallization. Then the pump is started, the oil is preheated, the oil is degassed, and the air is vented. Air venting is essential for correct test results. Without it, the readings will be unstable and distorted. Air removal is carried out in several iterations by means of a sequential change in the direction of flow through the impulse line. Then the temperature of the test section and feed tank is reduced to 25 °C, after which the temperature of the test section is reduced to the required temperature to simulate the wax deposition process.

The pressure in the installation is controlled by injecting nitrogen into the feed tank, and the temperature is controlled by circulating thermostats. This fact, in conjunction with the possibility of selecting the circulation rate of the studied fluid, and, therefore, achieving the required Reynolds number and shear stress, allows us to speak about the most correct modeling of wax formation processes in the field conditions.

In the course of the study (from 8 to 36 h), all data about the operation of this installation were automatically recorded, including temperatures in the feed tank, at the inlet and outlet of the test section, in the impulse line, pressure in the system, liquid flow rate, liquid density, and pressure drop between inlet and outlet of the test section. At the end of the study, a database was formed that includes changes in each parameter throughout the entire laboratory study. The data recording step was 20 s. The processing of this study consisted in determining the viscosity of oil and using the Poiseuille equation for the laminar flow regime according to Equation (3). Then this equation was transformed, the diameter value was moved to the left side, and the viscosity value was taken as a constant. According to this expression, it is possible to estimate the magnitude of the thickness of wax deposits at each moment of time. Figure 4 shows an example of a laboratory test processing result.

$$d = \left(\frac{Q \cdot 128 \cdot \eta \cdot l}{\pi \cdot P} \right)^{1/4} \tag{3}$$

where ΔP—pressure drop in the test section, MPa; Q—volumetric flow rate of the oil, m^3/s; η—viscosity of the oil, m^2/s; l—test section length, m; d—test section diameter, m.

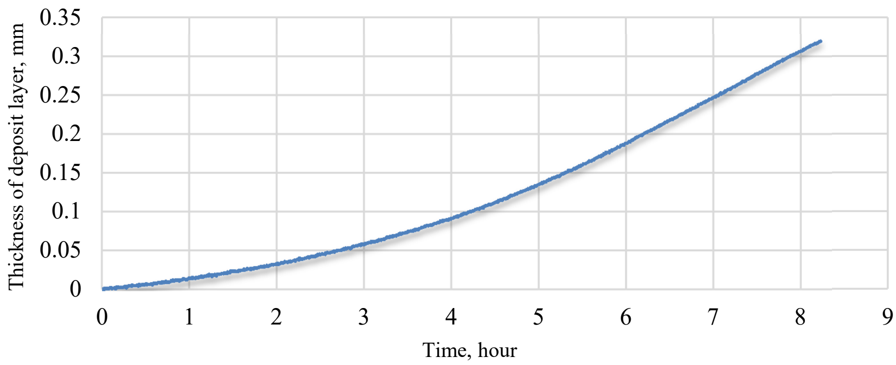

Figure 4. Dependences of the thickness of wax deposits on time.

The study of the kinetics of the formation of wax deposits at this installation in the presence of inhibitor reagents was carried out by dosing the calculated amount of reagent into the system through a bypass. After dosing of the inhibitor reagent, the fluid circulates in the system in the absence of a temperature gradient for uniform distribution of the reagent over the volume of oil.

A feature of the study of the kinetics of wax deposits formation on this laboratory installation, in contrast to the installation «Cold Finger», is the absence of a numerical determination of the intensive formation of wax deposits. Under these conditions, it becomes difficult to determine the specific value of the effectiveness of the investigated reagents-inhibitors. For this purpose, several methods have been developed for determining the value of the intensity of paraffin formation at the «WaxFlowLoop» installation. The following is a brief description of each of the developed methods:

Approximation by a linear law. When forming a linear law, it becomes possible to estimate the slope angle obtained by the curve. The ratio of these coefficients for the graphs of the formation of wax deposits with and without the use of an inhibitor reagent will reflect its technological efficiency.

Integration. Step-by-step integration enables calculation of the area under the graph, which allows one to consider all the data received. The effectiveness of the inhibitor reagents will be determined as the ratio of the area under the corresponding graphs.

Ratio of maximum thickness. The selection of the final section of the graph and comparison of the obtained thicknesses of wax deposits will also enable assessment of the effectiveness of wax scale inhibitors.

Within the framework of this laboratory study, four fluids were examined. Their physical and chemical properties are presented in Table 1.

Table 1. Physicochemical properties of the studied fluids.

Oil Field, Object		No. 1	No. 2	No. 3	No. 4
Volume factor, unit fraction		1.063	1.107	1.126	1.302
Content%	paraffin	3.51	3.46	3.67	3.73
	Resin and asphaltene	23.50	21.20	19.57	7.64
Density ρ_H, kg/m^3	degassed	885	862	850	823
	reservoir	865	830	806	740
Viscosity, mPac	degassed	14.73	15.53	16.42	3.37
	reservoir	12.27	3.75	3.71	1.44

For each of the presented fluids, several laboratory studies were carried out in the absence and presence of inhibitor reagents. Since the purpose of this work is only a comparative assessment of the old and new methods for assessing the effectiveness of wax deposition inhibitors, within the framework of this study, one inhibitor reagent with a dosage of 200 g/t was used. This reagent is an inhibitor of complex action and is a mixture of non-ionic and ionic surface-active components of domestic and foreign production in an alcoholic solvent.

3. Results

Figure 5 shows an example of a study of fluid No. 1 on the Wax Flow Loop installation.

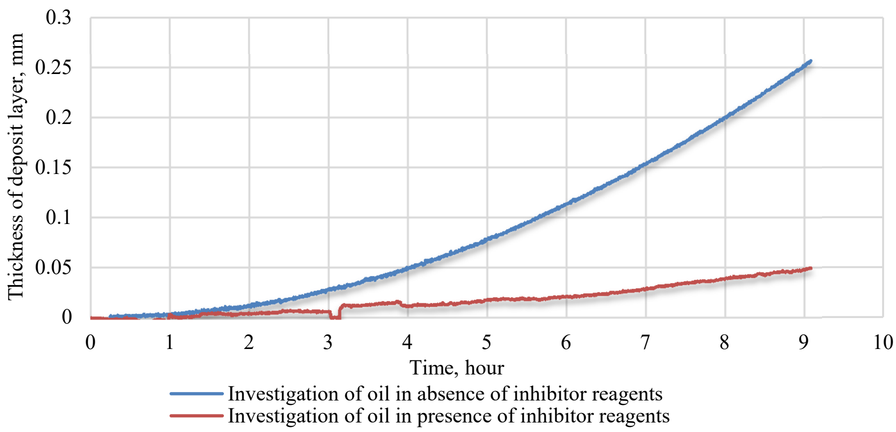

Figure 5. Dependences of the thickness of wax deposits on time.

Considering this graph, it can be noted that the rate of formation of wax deposits of a pure fluid significantly exceeds the rate of formation of these deposits when dosing an inhibitor reagent. It should be noted that the dynamics of changes in the thickness of wax deposits in these graphs differ from each other. In the case of studying a fluid with an inhibitor reagent, an increase in the thickness of wax deposits is also observed, but it is more linear. When considering the results of the study in the absence of a wax deposition inhibitor, the dynamics of changes in the thickness of wax deposits clearly deviate from the linear law. The most reliable approximation of this curve, when considering linear, logarithmic, power, and exponential laws, is obtained when using a power law, while the approximation coefficient is 0.988. The following are the results of using various methods for assessing the effectiveness of the inhibitor reagent described earlier.

The application of each of the methods is presented graphically in Figure 6.

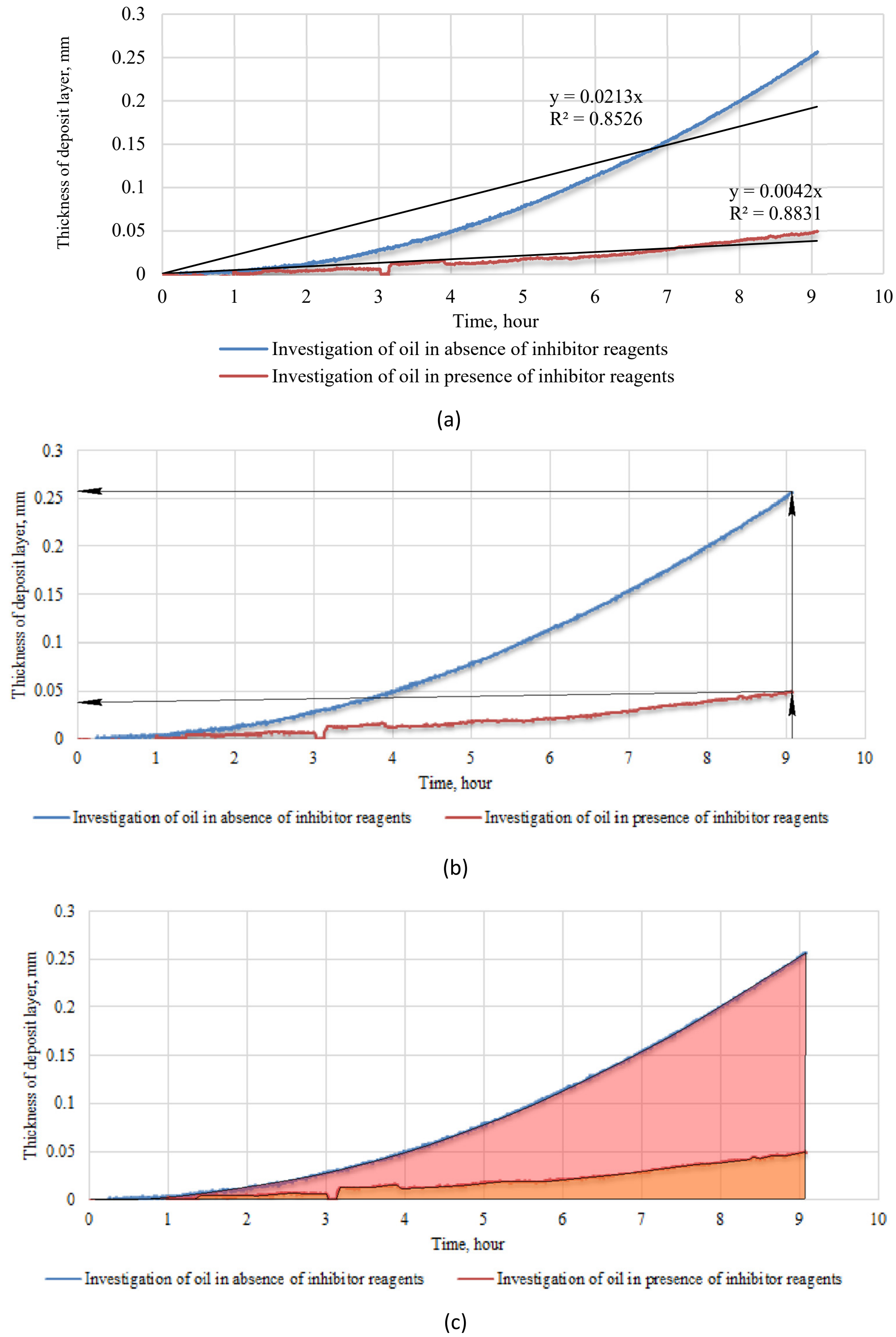

Figure 6. Graphic representation of methods for assessing the effectiveness of inhibitors: approximation by a linear law (**a**), the ratio of maximum thicknesses (**b**) and integration (**c**).

Considering Figure 6a, it can be noted that this method will be most effective at a linear rate of formation of wax deposits. This figure shows trend lines formed according to a linear law. However, based on the analysis of the base of laboratory studies, such a law is found in 10–15% of studies. This fact can be attributed to the disadvantage of this method. The method presented in Figure 6b makes it possible to evaluate the effectiveness of a laboratory study only with a proportional increase in the thickness of wax deposits in two compared studies; in other cases it is possible to obtain incorrect results. The lines shown in Figure 6b show the method of determining the maximum thickness (from the maximum study time). A common disadvantage of these methods is the lack of consideration of the dynamics of the thickness of wax deposits throughout the laboratory study. Analyzing Figure 6c, it can be seen that this method makes it possible to determine the effectiveness of the inhibitor reagent, taking into account all the data obtained as a result of laboratory research.

Table 2 shows the results of evaluating the effectiveness of the use of the reagent-inhibitor for each of the investigated oils by all the previously described methods. The result of the field assessment of the effectiveness of the considered reagent, carried out by analyzing the dynamics of the change in the inter-treatment period of the target object before and after the introduction of the considered reagent-inhibitor, is also given. The estimation of the value of the inter-treatment period consisted in the analysis of field data on the conduct of cleaning or repair activities at the target well and the determination of the time interval between them.

Table 2. Results of calculating the effectiveness of the inhibitor reagent in laboratory and field conditions.

Method		**Efficiency, %**			
		Fluid No. 1	**Fluid No. 2**	**Fluid No. 3**	**Fluid No. 4**
«Cold Finger»		26.68	25.51	50.51	43.77
«WaxFlowLoop»	Linear approximation	70.28	21.15	57.95	78.69
	Maximum thickness ratio	70.84	27.68	59.39	82.07
	Integration	79.54	13.17	64.74	85.37
Analysis of the dynamics of changes in the inter-treatment period		78.33	<15	66.66	88.10

It should be noted that it was impossible to determine the exact value of the change in the inter-treatment period for fluid 2. When using this reagent, no significant change in the inter-treatment period was observed, and therefore the dosing of this reagent was stopped. In general, considering the data obtained, it can be noted that the most correct laboratory research data are observed when assessing the effectiveness of wax inhibitors on the «WaxFlowLoop» installation. Among the methods of determination developed and described earlier, the method of integration can be considered the most correct. However, the determination of effectiveness by other methods also shows sufficient accuracy in each of the studies considered.

4. Discussion

As part of the studies, it was shown that there are several methods for studying the effectiveness of inhibitor reagents to prevent the formation of wax deposition. The most accurate is the method of integrating the wax formation curve used in the study of the fluid on the "WaxFlowLoop" installation. The obtained results of laboratory studies show that the reproduction of paraffin formation conditions significantly affects the result of evaluating the effectiveness of wax inhibitors. Moreover, when studying a fluid, it is necessary to take into account the entire curve of wax formation, which is confirmed by the "Maximum thickness ratio" method.

As can be seen from the results obtained, the results of studies of one fluid on the «WaxFlowLoop» and «Cold Finger» installations deviate significantly. This fact can be explained by different carbon number distribution of deposits for these laboratory installations. This parameter is influenced by many factors, including the temperature of the fluid and the speed of oil movement [38,39]. In [40,41], there was a simulated temperature distribution on the cross section in the «Cold Finger» installation. According to this distribution, the lowest temperature of the studied fluid is reached in the near-wall layer. The temperature in the rest of the fluid volume remains constant. Under these conditions, the fluid in the near-wall layer can be significantly supercooled, as a result of which heavier hydrocarbons can enter the sediments. It is also worth noting that the carbon number distribution of deposits is also influenced by the speed of fluid movement, which was experimentally confirmed in [42–44]. At the same time, in the «Cold Finger» installation, the linear velocity of fluid movement significantly changes over the volume of deposits due to the constancy of the peripheral speed and the increase in the radius of oil movement [45]. These disadvantages are absent when conducting studies on the «WaxFlowloop» installation: the volume of the studied fluid is regularly mixed and circulated through the system, preventing its excessive cooling, and the fluid velocity field in the laminar mode is more uniform [46].

Taking into account the indicated disadvantages, oil testing at the «Cold Finger» installation is an irrational method for determining an effective inhibitor reagent for the target fluid. Research at the «WaxFlowLoop» installation allows a more detailed reconstruction of the field conditions of sediment formation, which will allow the obtainment of a more correct carbon number distribution of deposits. The practical application of the presented methods for determining the effectiveness of wax inhibitors lies in the ability to most correctly assess the technological efficiency of the reagent for the target fluid, to select its dosage, and, thereby, to increase the operating efficiency of the production fund. It should be noted that the described technique is applicable only for single-phase liquid flows, which does not allow one to fully simulate the conditions of paraffin formation. The presence of free and dissolved gas or formation water in the produced and transported fluid can have a significant impact on the effectiveness of the use of inhibitor reagents.

Further research in this area can be aimed at determining the influence of the temperature regimes of the stand operation on the accuracy of assessing the effectiveness of wax deposition inhibitors, at developing and modernizing the above methods for assessing the effectiveness of these reagents, or at determining the limitations in the use of these techniques.

5. Conclusions

1. The formation of wax deposits is a complex process that has a significant impact on the operation of an oil production well. One of the most common methods of preventing their formation is the use of inhibitor reagents.
2. Evaluation of the effectiveness of the use of these reagents is carried out in laboratory conditions, and the most common method is the "Cold Finger". This method has a low accuracy, high error, and does not allow reproduction of the field conditions of wax formation. These disadvantages lead to an incorrect carbon number distribution of deposits and create additional errors in determining the effectiveness of inhibitor of wax deposits. The work proposes three methods for assessing the effectiveness of inhibitor reagents using the "WaxFlowLoop" installation.
3. In the course of laboratory studies, the method of integrating the paraffin formation curve was found. Comparison of laboratory research results with field data was carried out. The average deviation of the efficiency of wax inhibitors, determined using the «WaxFlowLoop» installation, is only 8.1%, and, for the values obtained on the «Cold Finger» installation, 200%.
4. The developed methods for determining the effectiveness of wax inhibitors make it possible to determine this value under conditions of paraffin formation, taking into account the entire volume of data obtained during laboratory research.
5. These results confirm the high accuracy of the developed methods and their significant superiority in comparison with the well-known «Cold Finger» method. The data

obtained can be used for a more correct selection of the brand of inhibitor reagents, their dosage, and, as a consequence, can increase the efficiency of the production well stock.

Author Contributions: Conceptualization, K.V. and P.I.; investigation, K.V. and A.K.; methodology, K.V. and A.K.; project administration, P.I.; resources, K.V.; software, A.K.; validation, A.K.; visualization, K.V.; writing—original draft, K.V. and A.K.; writing—review and editing, P.I. All authors have read and agreed to the published version of the manuscript.

Funding: The work was carried out in the organization of the Lead Contractor as part of the R & D, carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation (agreement number 075-11-2021-052 of 24 June 2021) in accordance with the decree of the Government of the Russian Federation: 09.04.2010, number 218 (PROJECT 218). The main R & D contractor is Perm National Research Polytechnic University.

Conflicts of Interest: The authors declare no conflict of interest.

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