RESEARCH NOTE

Development of a Method for Estimating Thermal Conductivity of Organic Deposits on the Wax Flow Loop Laboratory Installation

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A B S T R A C T

During the oil production, the occurrence of such a complication as the formation of wax deposits is not uncommon. The fight against these deposits, as well as the development of modern methods of dealing with them, is one of the most important tasks of the subsoil user. Many modern methods of modeling deposits require the exact determination of such a quantity as the thermal conductivity of organic deposits. Based on the analysis of scientific literature, it can be concluded that there is no method developed for estimating this value under conditions of wax formation without affecting their pore structure. The paper describes a method for determining this value based on the results of a study of the process of formation of organic deposits on the laboratory installation "Wax Flow Loop" based on the laws of heat and mass transfer. Based on the results of applying this technique, it becomes possible to determine the thermal conductivity of organic deposits, the value of which correlates with the values given in the reference and scientific literature. In addition, the presence of a correlation between the value of the thermal conductivity of deposits and the component composition of the studied fluid was determined. The application of the described technique will make it possible to most accurately simulate the processes of oil production and determine the technological effectiveness of the use of modern methods of combating organic deposits.

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NOMENCLATURE

C_T	heat capacity of oil (J/(kg· °K))	υ	flow rate (m/s)
d_1	inner diameter of the test section before wax deposition (m)	**Greek Symbols**	
d_2	outer diameter of the test section (m)	α	coefficient of heat transfer from the fluid to the wall (W/($m^2 \cdot °K$))
d_3	inner diameter of the test section after the formation of organic deposits (m)	β	temperature coefficient of volumetric expansion (deg^{-1})
Gr	Grashof number	ΔP	pressure drop in the test section (MPa)
g	acceleration due to gravity (m/s^2)	ΔT	difference between the cooling temperature of the test section and the temperature at the outlet of the test section (℃)
l	pipe length (m)	η	viscosity of the oil (m^2/s)
Nu	Nusselt number	λ_T	thermal conductivity of oil (W/(m· °K))
Pr	Prandtl number	λ_{steel}	coefficient of thermal conductivity of the test section material (W/(m· °K))
Pr_s	Prandtl number at wall temperature	λ_{wax}	coefficient of thermal conductivity of wax deposits (W/(m· °K))
Pr_{oil}	Prandtl number at the temperature of oil at the outlet of the test section	μ	kinematic viscosity of the liquid at average temperature, mPa·s;
Q	volumetric flow rate of the oil (m^3/s)	ν	kinematic viscosity of the liquid (m^2/s)

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q_l	value of the linear heat flux density (W/m)	$\sum(C_{17} - C_{60})$	total content of high weight components in oil (%)
Re	Reynolds number	$\sum(C_5 - C_{16})$	total content of low molecular weight components in oil(%)
R_l	thermal resistance of test section befor formation of wax deposition ((m· °K) / W)	π	number Pi
R_l^*	thermal resistance of test section after formation of wax deposition ((m· °K) / W)	ρ_{15}^{15}	relative density of oil at a temperature 15℃ (kg/m^3)
T	temperature at the entrance to the test section (°К)	ρ	density of the fluid (kg/m^3)

1. INTRODUCTION

Most of the oil fields in the Russian Federation and, in particular, the Perm Krai are entering the final stages of development [1]. In addition to a decrease in oil production rates and an increase in the water cut of the produced liquid, intensification of the processes of formation of asphalt-resin-paraffin deposits (ARPD) is observed in these fields [2]. The formation of these deposits causes a decrease in the hydraulic radius of the production string, an increase in pressure in the oil gathering system and a decrease in the service life of oilfield equipment [3].

At the present time, there are many methods of dealing with these deposits, but all these methods can be divided into two groups: prevention of the formation of deposits and their removal [4,5]. There is also a classification based on the active physical field: chemical, mechanical, physical and thermal [6]. The most widespread, at the moment, among the technologies for removing organic deposits are various scrapers, treatment of a well or an oil pipeline with hydrocarbon solvents, hot oil or water [7,8]. Among the methods for preventing the formation of deposits are the dosage of wax deposits inhibitors, the use of smooth coatings on the inner surface of the tubing and heating cables [9,10]. Also, many modern methods of dealing with deposits find their place in oil production, among which we can identify the technology of the "controlled layer", oil treatment with ultrasound, selection of the speed mode of the well, etc. [11-13]. As part of the review of the scientific literature, it was noted that for the application of these methods, the required value is the thermal conductivity of organic deposits.

An important note is the need to assess the thermal conductivity of organic deposits without physical impact on their pore structure. The volume of these deposits is heterogeneous in its properties, deposits can have different porosity values, and the pore space is filled with various fluids [14].

At the same time, in many scientific publications, including literature [15,16], this value was taken equal to a constant, the justification for which was not given.

In the modern oil industry, there is a strong trend towards the digitalization of production, including the development and implementation of "digital twins" of fields and computer modeling of oil production and transportation processes. For the successful implementation of these technologies, it is necessary to have a large amount of data on the properties of fluids, the laws of their flow and heat and mass transfer. So, for example, in the well-known methods for determining the temperature of the inner surface of the tubing string, the processes of paraffin formation and related changes in the heat and mass transfer regime are not taken into account [17,18]. To take into account these changes, it is required to use not only more modern methods for determining the temperature of the production wellbore but also a number of studies to determine the actual thermal conductivity of organic deposits. This fact confirms the importance of this parameter for the process of modeling the fluid flow along the production wellbore.

Another important trend in modern oil production is the environmental friendliness of the field. In this regard, new methods are being developed for using oilfield waste, including paraffin deposits. Their use is possible as thermal insulation, as part of the road surfaces and for petrochemical purposes [19,20]. All these areas require a deep study of the properties and composition of the formed deposits, including their thermal conductivity.

Modeling of wax formation processes is also of fundamental importance in the design of production and transportation of formation fluids. The assessment of the probability of formation of these deposits and the nature of their distribution along the length of the production tubing or linear oil pipeline makes it possible to assess the need to apply methods to combat wax deposits for the trouble-free operation of oilfield equipment.

Modeling of the processes of formation of organic deposits occurs in various software systems using a variety of models for the formation of these deposits. Most of the models described in the scientific literature take into account the composition of the fluid, the thermobaric and velocity conditions of its flow [21]. A common parameter taken into account in all considered models is the presence of a temperature gradient between the fluid flow and the cold surface. However, when modeling the processes of formation of organic deposits, the thermal conductivity of these deposits, which can have a significant impact on the kinetics of this process, is not taken into account. Veiga et al. [22], Sousa et al. [23], they have demonstrated that the thermal resistance of organic deposits is the dominant resistance when the thickness of organic deposits reaches 5% of the pipe diameter. As a result of modeling the thickness of organic deposits in the annular geometry of the laminar flow, it

was found that a change in the thermal conductivity of organic deposits from 0.1 to 0.4 W/(m·°K) leads to a change in the thickness of wax deposits by 50%, which confirms the importance of this parameter in modeling paraffin formation.

Based on the foregoing, it becomes obvious that for the most detailed modeling of the processes of oil production and transportation, as well as the introduction and assessment of the technological efficiency of the modern methods of combating organic deposits, it is necessary to develop a method for determining the thermal conductivity of organic deposits. This work presents a method that allows estimating this value with sufficient accuracy in the study of the process of organic deposits formation on the laboratory installation "WaxFlowLoop".

2. MATERIALS AND METHODS

The "WaxFlowLoop" laboratory installation is a closed hydraulic circuit for studying the process of paraffin formation. This unit as an experimental setup is shown in Figure 1. The principle of operation of the installation is to constantly maintain the temperature of the test fluid circulating through the system and to cool the test section to create a temperature gradient between the flow and the wall. The pressure in the system is set due to the injection of nitrogen into the feed tank through a special channel (not shown in the figure).

Conducting research on this installation involves simulating the movement of fluid in a real oil pipeline. The achievement of this goal is provided by kinematic, thermal and technological similarities. The kinematic is provided by controlling the mass flow rate of the oil in the test section by means of frequency control of the motor. Thermal similarity is provided by setting the required oil and test section temperatures. Technological similarity means the study of the real fluid, as well as the

execution of the test section of their stainless steel. Providing these similarities allows us to speak about the similarity of the modes of formation of organic deposits in the test section and in a real oil pipeline.

During the operation of this laboratory installation, in order to simulate the process of fluid transportation in a real pipeline, the mass flow rate of the pump is selected based on the requirements for observing kinematic similarity. Compliance with this requirement, as well as the execution of the test section from stainless steel and correct sampling, allows us to speak about the similarity of the conditions for the formation of organic deposits in the considered laboratory stand and the real pipeline. As part of this work, studies were carried out under the laminar regime of fluid flow in the test section.

During the study, many different parameters are recorded, among them: pressure drop between the inlet and outlet of the test section, temperature at the inlet and outlet of the test section, oil mass flow rate, oil density, temperature in the installation and thermostats, etc. The study on this installation lasts from 8 to 36 hours with regular registration of these parameters. At the end of the study, a database is formed that reflects the change in all the values described above over time. Based on these data, it becomes possible to determine the thickness of organic deposits at each moment of the time, for this we write expression 1, which is the Poiseuille equation, which is a special case of the Darcy-Weisbach formula for the laminar flow regime when calculating pressure losses in the pipeline [24].

$$\Delta P = \frac{Q \cdot 128 \cdot \eta \cdot l}{\pi \cdot d_1^{\,4}} \tag{1}$$

Transforming this expression, we get expression 2, which is an expression for determining the internal diameter of the test section.

$$d_1 = \left(\frac{Q \cdot 128 \cdot \eta \cdot l}{\pi \cdot \Delta P} \right)^{1/4} \tag{2}$$
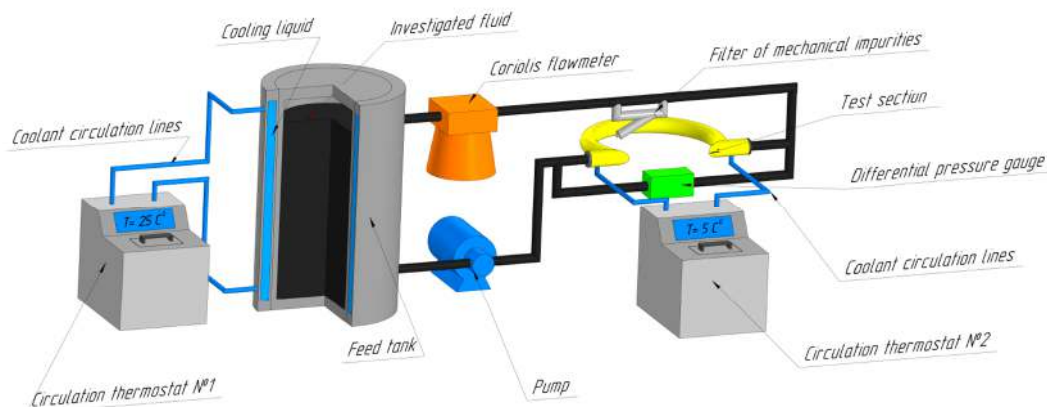

Figure 1. Laboratory installation "WaxFlowLoop"

For a reliable assessment of the thermal conductivity of organic deposits, it is necessary to know the dynamics of changes in the temperature of the inner surface of a particular point of the test section; however, this installation will only allow estimating the temperature at the outlet of the test section. To determine the correctness of taking this temperature as the temperature in the test section, modeling was carried out in the Ansys Fluent software package. The simulation results are shown in Figure 2.

From the modeling results, it becomes obvious that the flow temperature drops sharply at the entrance to the test section and its further decrease can be taken as insignificant. As a result, the temperature at the point of the test section in this method will be taken as the temperature at the outlet of the test section.

It is also important to note that in order to determine the thermal conductivity, it is necessary that all data recorded during the study change linearly, and the mass flow rate, the temperature at the inlet to the test section and in circulation thermostats change by no more than 5%. This value was obtained during laboratory tests and interpretation of their results.

To assess the thermal conductivity, the following initial data are required: the dynamic viscosity of oil at the temperature to which the test section is cooled and the test fluid is heated, the density of the mixture at the beginning of the study, the temperature at the inlet to the test section, the cooling temperature of the test section, at the outlet of the test section at the beginning of the study and finally, the thickness of organic deposits on the wall of the test section, the mass flow rate of the test fluid through the test section, the inner and outer diameters of the test section before paraffin formation, the thermal conductivity of the test section material, the thermal expansion coefficient of the oil.

The first step is to determine the thermal conductivity and heat capacity of the oil according to the empirical formulas of Craig, presented in expressions 3 and 4, respectively [25].
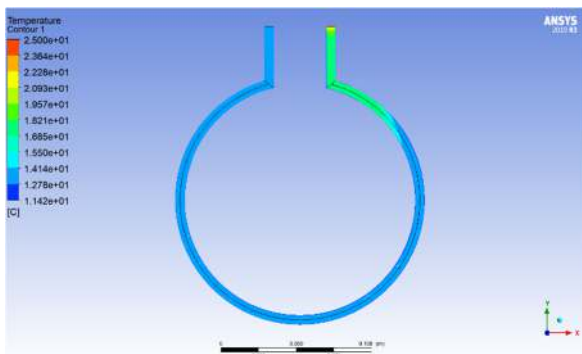

Figure 2. Modeling the temperature distribution in the test section during laboratory research

$$\lambda_T = \frac{0,00117}{\rho_{15}^{15}} \cdot (1,1474 - 0,00054 \cdot T) \tag{3}$$

$$C_T = \frac{1,687 + 0,00339 \cdot T}{\sqrt{\rho_{15}^{15}}} \tag{4}$$

After determining these parameters, it is necessary to determine a number of criteria for hydrodynamic and thermal similarity, namely: Reynolds, Prandtl and Grashof, the formulas for determining which are presented in expressions 5-7, respectively. Based on the obtained data values, the criterion is to select a formula to determine the Nu. Within the framework of this installation, it is proposed to use the formula given in expression 8.

$$Re = \frac{v \cdot d_1}{\nu} \tag{5}$$

$$Pr = \frac{C_T \cdot v \cdot \rho}{\lambda_T} \tag{6}$$

$$Gr = \frac{g \cdot \beta \cdot d_1^{\ 3}}{\nu^2} \cdot \Delta T \tag{7}$$

$$Nu = 0,5 \cdot Re^{0.33} \cdot Gr^{0.1} \cdot Pr_{\text{oil}}^{\ 0,43} \cdot \left(\frac{Pr_{\text{oil}}}{Pr_s}\right)^{0,25} \tag{8}$$

Taking into account the known value of the Nusselt coefficient, it becomes possible to determine the heat transfer coefficient from the fluid to the wall, presented in expression 9.

$$\alpha = \frac{Nu \cdot \lambda}{d_1} \tag{9}$$

Using this coefficient, we determine the value of the linear thermal resistance of heat transfer through the cylindrical wall (R_l) and the value of the linear heat flux density (q_l), according to expressions 10 and 11, respectively. It should be noted that the application of the classical Fourier heat transfer equation is due to the slow change in the temperature gradient and flow in the test section of the Wax Flow Loop installation [26]. In expression 11, the heat transfer coefficient from the test section to air is not taken into account due to its insignificant value and the high complexity of the calculation.

$$R_l = \frac{1}{\alpha \cdot d_1} + \left(\frac{1}{2\lambda_{steel}} \cdot ln\frac{d_1}{d_2}\right) \tag{10}$$

$$q_l = \frac{\pi \cdot \Delta T}{R_l} \tag{11}$$

Having determined the value of the linear density of the heat flux, it is necessary to take it as a constant for a given operating mode of the installation since the heat transfer mode remains stationary and the heat flux remains unchanged. Accordingly, in the process of formation of organic deposits, as the thermal resistance of the test section changes, due to the formation of

organic deposits, the temperature gradient will also change. Let us write expression 12, which reflects the change in the value of thermal resistance after the formation of organic deposits.

$$R_l^* = \frac{1}{\alpha \cdot d_1} + \left(\frac{1}{2\lambda_{steel}} \cdot ln\frac{d_1}{d_2}\right) + \left(\frac{1}{2\lambda_{wax}} * ln\frac{d_2}{d_3}\right) \quad (12)$$

Having transformed expression 11, taking into account expression 12, we write the formula for determining the thermal conductivity of organic deposits in the form of expression 13.

$$\lambda_{wax} = \frac{ln\frac{d_2}{d_3}}{2 \cdot (R_l^* - R_l)} \quad (13)$$

The method presented in this work allows us to evaluate the thermal conductivity of organic deposits without the use of additional research methods, but only based on the results of assessing the kinetics of wax deposits formation at the "WaxFlowLoop" installation.

The assumption of the application of this technique is the uniform distribution of the thickness of organic deposits along the length of the test section, since it is not possible to assess the actual profile of the adhered deposits. However, it should be noted that if there is an uneven distribution of organic deposits in the test section, this will not significantly affect its total thermal resistance.

3. RESULTS AND DISCUSSIONS

As an illustration of the work of this method, we present the processing of data from a real laboratory study. The initial data for processing are presented in Table 1.

Graphs reflecting the change in the main parameters of the study are shown in Figure 3.

TABLE 1. Parameters of laboratory research

Parameter		Dimesion	Value
Dynamic vicosity of oil	20 ℃	mPa·s	32.25
	5 ℃		96.7
Oil density		kg/m3	885.12
Thermal conductivity of the test section material		W/(m· °K)	90
Mass flow rate of liquid		kg/h	4.0
Temperature at the outlet of the test section	At the start of the study	℃	13.81
	At the end of the study	℃	15.21
Cooling temperature of the test section		℃	5
Thickness of organic deposits at the end of the study		mm	0.495

As a result of processing this study, it was obtained that the average thermal conductivity of organic deposits is 0.247 W/(m·°K). Due to the fact that there were no available methods, techniques or empirical dependencies to determine this value, a comparison of this value with tabular values was carried out. The value obtained by the team of authors slightly differs from that given in the reference literature, which can be explained by differences in the fractional and component composition of the studied deposits.

This paper presents the results of processing a number of laboratory studies to determine the thermal conductivity of wax deposits (Figure 4). These studies were carried out on 20 formation fluid samples. These oils were selected from various production wells in the Perm Krai. The fractional composition was determined by gas chromatography for each of the studied fluids. In order to characterize the fractional composition of the fluid by one parameter, a value characterizing the ratio of low-molecular and high-molecular components in the studied fluid was developed. The formula for calculating this value is presented in expression 14. The results of determining this correlation dependence are shown in Figure 4.
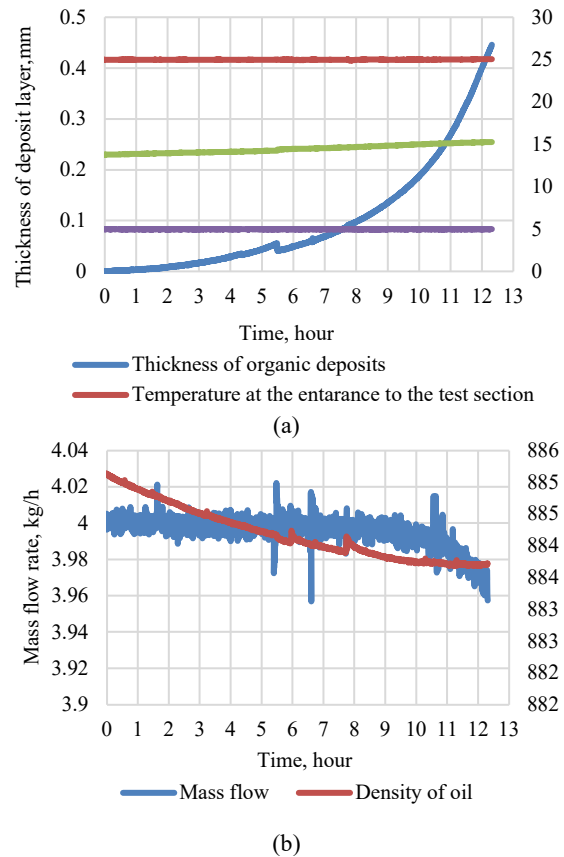

(a)

(b)

Figure 3. Changes in the operating temperature of the installation and the thickness of organic deposits (a), density and flow rate of the liquid (b)
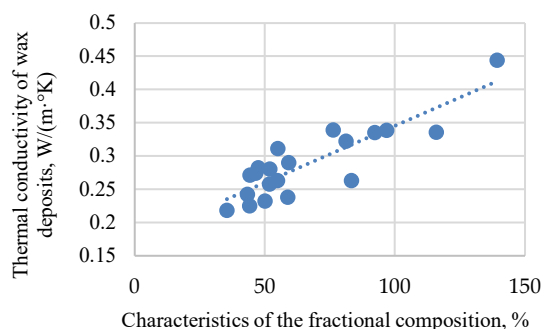
Figure 4. Dependence of wax deposits thermal conductivity on characteristics of fractional composition

$$X = \frac{\sum(C_5 - C_{16})}{\sum(C_{17} - C_{60})} * 100\% \qquad (14)$$

As can be seen from Figure 4, for the studied oils, the fractional composition characteristic is in the range of 35.4% to 139.1%. Analyzing the nature of the change in thermal conductivity, it is worth noting that there is a steady upward trend in this value with an increase in the characteristics of the fractional composition in the entire considered range. The presence of this dependence indicates a lower value of the thermal conductivity coefficient for heavy oils, which is explained by the content of high concentrations of resins and asphaltenes in them.

In addition to this parameter, the dependence between the thermal conductivity of wax deposits and the viscosity of the fluid under study is determined. This correlation is substantiated by a significant effect on the fluid viscosity of the content of high-molecular components. As is known, the thermal conductivity of hydrocarbons of the methane series decreases with increasing molecular weight, which is generally confirmed by this dependence shown in Figure 5.
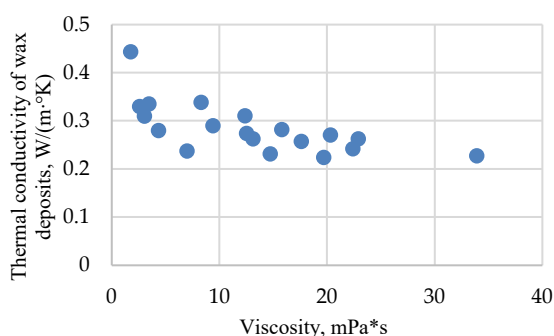

Figure 5. Dependence of wax deposits thermal conductivity on fluid viscosity

Analysis of Figure 5 confirms the theory of the influence of fluid composition on the thermal conductivity of wax deposits. The high content of heavy components causes an increase in fluid viscosity and a decrease in its thermal conductivity. The obtained correlation dependence confirms the previously put forward assumptions and shows that the estimation of the thermal conductivity of organic deposits is possible, including the results of fluid rheological studies, without carrying out an expensive study of the fractional composition.

The developed method makes it possible to determine the thermal conductivity of organic deposits in the process of paraffin formation, without changing their pore structure. The use of this method will make it possible to estimate this value with sufficient accuracy, which will allow the most accurate modeling of wax formation, the temperature of the inner surface of the production tubing and a linear oil pipeline. A feature of this method can be considered the conduct of research in a laminar mode and the study of exclusively degassed formation samples; however, this is a limitation of the laboratory installation. Determination of the correlation dependences between the thermal conductivity of wax deposits and the characteristic of the fractional composition will make it possible to estimate this value more correctly without carrying out long laboratory studies. Further research in this area can be aimed at influencing the thermal conductivity of organic deposits, the temperature of their formation, the presence of inclusions of oil and water phases.

4. CONCLUSIONS

As a result of the work performed, in the following should be noted:
1. The authors have developed a previously absent method for determining the thermal conductivity of organic deposits under conditions of paraffin formation without physical impact on the pore structure of deposits.
2. The value obtained as a result of the implementation of this method correlates with the data given in the referred literature.
3. Analysis of studies indicates the presence of a correlation between the thermal conductivity of deposits and the composition and properties of the initial fluid, as a result of which its assessment is possible without additional laboratory studies.
4. The application of the above methodology is possible to increase the accuracy of modeling the process of formation of organic deposits or the introduction of modern methods to combat these deposits.

5. ACKNOWLEDGEMENTS

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Persian Abstract

چکیده

در طول تولید نفت، بروز چنین عارضه ای مانند تشکیل رسوبات موم غیر معمول نیست. مبارزه با این رسوبات و همچنین توسعه روش های نوین مقابله با آنها از مهمترین وظایف بهره برداران از زیر خاک است. بسیاری از روش‌های مدرن مدل‌سازی نیاز به تعیین دقیق عددی مانند هدایت حرارتی رسوبات آلی دارند. بر اساس تجزیه و تحلیل متون علمی، می توان نتیجه گرفت که هیچ روشی برای تخمین این مقدار در شرایط تشکیل موم بدون تأثیر بر ساختار منافذ آنها وجود ندارد. این مقاله روشی را برای تعیین این مقدار بر اساس نتایج مطالعه فرآیند تشکیل رسوبات آلی در تاسیسات آزمایشگاهی "حلقه جریان موم" بر اساس قوانین انتقال حرارت و جرم توصیف می کند. بر اساس نتایج به کارگیری این تکنیک، تعیین رسانایی حرارتی رسوبات آلی امکان پذیر می شود که مقدار آن با مقادیر ارائه شده در منابع مرجع و علمی مرتبط است. علاوه بر این، وجود یک همبستگی بین مقدار هدایت حرارتی رسوبات و ترکیب اجزای سیال مورد مطالعه تعیین شد. استفاده از روش توصیف شده این امکان را به شما می دهد که فرآیندهای تولید نفت را با دقت بیشتر شبیه سازی کنید و اثربخشی تکنولوژیکی استفاده از روش های مدرن مبارزه با سوب گذاری مواد آلی نظیر موم را تعیین کنید.