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Utilizing low-frequency ultrasound as a countermeasure to asphalt-resin-paraffin deposition in oil pipelines

Nazarenko Ivan[1]*, Nesterenko Tetiana[2], Nesterenko Mykola [3], Bernyk Iryna[4]

[1] Kyiv National University of Construction and Architecture https://orcid.org/0000-0002-1888-3687
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-2387-8575
[3] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-4073-1233
[4] Vinnytsia National Agrarian University https://orcid.org/0000-0002-1367-3058
*Corresponding author E-mail: i_nazar@i.ua

The experimental data on the low-frequency ultrasound effect on asphalt-resin-paraffin deposits (ARPD) occurring in oil transportation through pipelines are presented. As a result of the empirical data statistical processing, a correlation was obtained, which enables the prediction of the ultrasonic exposure time required to remove ARPD from the surface of the pipes. The temperature regime changed from the time of ARPD formations exposure to the ultrasonic influence was analyzed. The proposed algorithm for finding the ultrasonic treatment optimal operational parameters can be used not only in the selection of ultrasonic equipment parameters, which control ARPD in pipelines but also in the run-in hole ultrasonic equipment's operating parameters selection in certain fields conditions

Keywords: asphalt-resin-paraffin deposits, oil pipeline, temperature conditions, ultrasound, ultrasonic equipment

Використання ультразвуку низької частоти як методу боротьби з асфальто-смоло-парафіновими відкладеннями у нафтопроводах

Назаренко І.І.[1]*, Нестеренко Т.М.[2], Нестеренко М.М.[2], Берник І.М.[4]

[1] Київський національний університет будівництва та архітектури
[2] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[3] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
[4] Вінницький національний аграрний університет
*Адреса для листування E-mail: i_nazar@i.ua

Проаналізовано існуючі методи механічного, теплового та хімічного впливу на асфальто-смоло-парафінові відкладення (АСПВ). Виявлено, що незважаючи на велику кількість робіт про парафінізацію трубопроводів, які транспортують нафту і нафтопродукти (магістральні трубопроводи, місцеві трубопроводи, шлейфи свердловин, внутрішньопромислові трубопроводи), та про методи боротьби з АСПВ, метод ультразвукової обробки вивчений недостатньо повно. Проведено лабораторні дослідження впливу ультразвукових хвиль низької частоти на АСПВ зі шлейфа нафтової свердловини. Наведено дані експериментальних досліджень впливу ультразвукових хвиль низької частоти (20 – 40 кГц) на АСПВ, що виникають при транспортуванні нафти та нафтопродуктів по трубопроводах. Отримано залежність у результаті статистичної обробки експериментальних даних, яка дає можливість прогнозувати час ультразвукового впливу, необхідний для видалення АСПВ від поверхні трубопроводів, що транспортують нафту та нафтопродукти. Визначено, що найбільший вплив на масу видалених АСПВ має час ультразвукової взаємодії. Проаналізовано зміну температурного режиму під часу ультразвукового впливу на асфальто-смоло-парафіністі відкладення. Застосовано метод комплексного впливу кавітуючого поля та теплового ефекту від ультразвукових хвиль (сферична модель розповсюдження теплових та ультразвукових хвиль) для отримання залежності, що дозволяє визначити прогнозований перепад температури, за якого відбудеться видалення АСПВ. Запропоновано алгоритм пошуку оптимальних параметрів режиму ультразвукової обробки, який може бути використаний не тільки при підборі параметрів роботи ультразвукового обладнання, яке застосовується для боротьби з АСПВ у трубопроводах , а і для обладнання, яке спускається безпосередньо у свердловину

Ключові слова: асфальто-смоло-парафінові відкладення, нафтопровід, температурний режим, ультразвук, ультразвукове обладнання

Introduction

Asphalt-resin-paraffin depositions (ARPD) are one of the problems that cause complications in the operation of technological equipment, tanks, and pipelines in the production, collection, transportation, and storage of oil.

The accumulation of ARPD in the pipelines leads to a sharp drop in system performance – increased pressure drops and reduced capacity. Nowadays, there are many methods of combating ARPD oil, most of which are based on thermochemical methods, the use of which is associated with high costs and reduced safety of work performed [1–3].

Existing methods of purely mechanical impact do not give high positive results in pipelines, because the usual flow rates do not provide the necessary effort to affect the scrapers on the dense layers of ARPD. Experience in vibration treatment of highly paraffinic oils has shown a negative effect on the durability of pipeline systems' structural elements.

Thus, at present, there are no effective, safe, and environmentally friendly methods of ARPD removal at oil pipelines.

Review of the research sources and publications

Thermal, chemical, and mechanical methods of ARPD removal are used in oil production. Thermal methods are based on the paraffin tendency to melt at temperatures exceeding 50 °C and drain from the heated surface. Creating the necessary temperature requires a special heat source that can be placed directly in the area of depositions [4 – 6].

Currently, technologies are utilizing: hot oil or water as the heat carrier; steam; ground & downhole electric furnaces; induction flow heaters; reagents in the interaction of which exothermic reactions occur.

The disadvantages of these methods are their high energy consumption, electrical and fire hazard, unreliability, and low efficiency of the applied technologies. The use of solvents to remove deposits that have already formed is one of the most well-known and widespread methods in the technological processes of production, transportation, storage, and refining of oil.

However, the problem of solvent selection for specific conditions is far from being solved. As a rule, the selection of ARPD solvents is carried out empirically. This is due to the lack of information about their structure and properties, as well as the insufficient mechanism knowledge of the petroleum dispersed system interaction with solvents.

Mechanical methods involve the removal of already formed ARPD deposits. A number of various design scrapers have been developed for this purpose.

The use of ARPD control methods is greatly complicated by the fact that its use often requires the pipeline's shutdown.

The method of using coatings gave a generally positive effect, but the high cost of pipe production with enamel and epoxy coating did not allow the coated pipes to be used. Today the application of this method is very limited.

A large number of scientific papers are devoted to the mechanism of magnetic oil treatment, water-oil, and water systems. The theory of magnetic influence on liquid media containing impurities of ferromagnetic particles is proposed.

Definition of unsolved aspects of the problem

Problems of the ultrasonic technologies research for application in the oil and gas industry were addressed in the following papers [7 – 9]. Most of the research has been done in the last two decades and lacks requirements and recommendations for the use of ultrasound equipment for ARPD removal. Also, the authors of [8, 9] approached the use of ultrasound mainly to intensify the impact on the bottom-hole zone of the well; the use of it to clean the pipelines was not given due attention.

Despite a large number of papers on the paraffinization of main oil pipelines and counter measuring ARPD methods, the method of ultrasonic treatment is not fully understood. However, in the transportation and storage of oil in the systems of collection and pipeline transport, the paraffinization problem has always remained a priority.

Problem statement

Therefore, the research aims to study the efficiency and feasibility of ARPD treatment with ultrasonic waves.

To achieve this, the following tasks are set: experimental studies of ultrasound influence on ARPD samples; obtaining a relationship between the mass of ARPD, the time of ultrasonic treatment, and the frequency of ultrasonic waves; based on experimental studies, obtaining the dependence to determine the optimal time for ultrasonic treatment.

Basic material and results

The mechanism of the ultrasound impact is still insufficiently studied [10, 11], so, at this time, it is impossible to assess how the melting of ARPD occurs due to ultrasonic waves.

To study the effect of ultrasonic waves on ARPD, a multifactorial experiment was performed on metal samples (fig. 1).

Figure 1 – Sample before experimental research

Metal plates were used as samples, which were weighed on electronic scales before applying ARPD on them. Then ARPD was applied to the plates in the same amount.

A sampling of ARPD and their analysis was performed directly during the technical diagnostics of wells. The component composition of the plug was determined in the laboratory by the standard method.

Table 1 presents the component composition of the samples taken from the well of PJSC "Ukrnafta". Type ARPD P/S+A – paraffinic.

In table 1 take the following notation: p-n – paraffin-naphthenic hydrocarbons; l-a – light aromatic hydrocarbons; m-a – medium aromatic hydrocarbons; h-a – heavy aromatic hydrocarbons; resins I – benzene resins; resins II – alcohol-benzene resins.

The samples were placed in an ultrasonic cleaner, the study was performed according to the parameters of the planning matrix of the experiment (Table 2). At the same time, variation of 2 factors was carried out: ultrasonic influence with an interval of 10, 15, 20 minutes and frequencies of 20, 30, and 40 kHz. Let us denote the factors: time – t (factor №1) and frequency of sound – f (factor №2).

After each experiment, the sample was dried and weighed again (Fig. 2). The difference in ARPD mass before and after the experiment gives the mass of ARPD detached from the surface. As a result of the experiment, there was the percentage of destroyed ARPD from the total mass of the applied ARPD entered in the table.

Samples after examination were photographed and magnified on an electron microscope (fig. 3-5).

Figure 2 – Sample after short-term exposure to ultrasound

Figure 3 – Sample after prolonged exposure to ultrasound

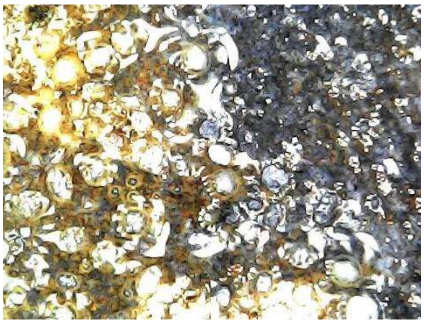

Figure 4 – Magnification of the sample under the microscope immediately after the examination (with cavitation bubbles)

Figure 5 – Magnification of the sample under the microscope

Table 1 – The results of the hydrocarbon type content studies ARPD

Composition, %							
Hydrocarbons				Resins I	Resins II	Asphaltenes	Paraffin
p-n	l-a	m-a	h-a				
39,2	17,1	11,2	14,7	5,6	10,8	1,4	14,6

Table 2 – Experiment planning matrix 3^2

Experiment #	Factor №1			Factor №2		
	-1	0	+1	-1	0	+1
1	10			20		
2	10				30	
3	10					40
4		15		20		
5		15			30	
6		15				40
7			20	20		
8			20		30	
9			20			40

As a result of experimental data statistical analysis, the correlation (1) and graphs of functions were obtained (fig. 6, 7). The results' probability of exceedance is R=0.975.

The equation for determining the mass of destroyed ARPD taking into account the paired linear and quadratic interactions has the following form

$$m = 0.347 + 0.204t + 0.126f - 0.048t_1^2 + 0.07tf \; . \quad (1)$$

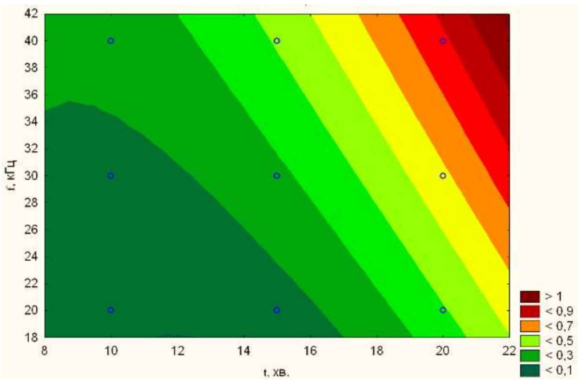

Figure 6 – Cross-section of the ARPD response surface (in fractions)

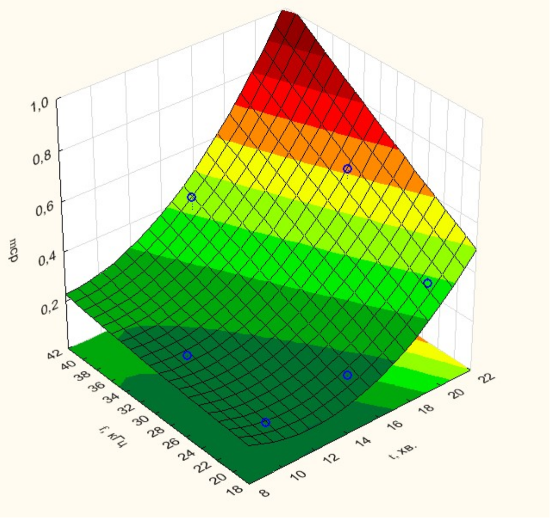

Figure 7 – Correlation of the amount of ARPD versus the frequency and time of ultrasonic interaction

To assess the effect of ultrasound on the purification process from ARPD, it's needed to use a well-known method that accounts for the complex effect of the cavitation field and the thermal effect of ultrasonic waves [12].

A mathematical description of one of the effect hypotheses will be offered next, taking into account the experimental studies' results.

It has been experimentally established that ARPD deposits are simultaneously affected by 2 effects: thermal effect and ultrasonic waves effect.

Heat distribution simulation is well studied and known equations are used for this process. We assume that we will further analyze the spherical model of thermal and ultrasonic wave propagation.

Heat distribution in spherical coordinates is

$$\frac{\partial T}{\partial t} = -\frac{\lambda}{\rho \cdot c_v}\left[\frac{1}{r^2} \cdot \frac{\partial}{\partial r}\left(r^2 \cdot \frac{\partial T}{\partial r}\right)\right], \qquad (2)$$

where T – ARPD temperature in the studied volume;
r – coordinate in spherical coordinates;
ρ –ARPD density;
λ – thermal conductivity index.

Assuming that the increase in temperature is due to the power of thermal radiation in the ultrasonic emitter, it is possible to add a boundary condition

$$\frac{\partial T}{\partial r_{r=r_0}} = \frac{Q}{\lambda F}, \qquad (3)$$

where Q – heat source capacity;
F – the surface area of the heat source;
r_0 – conditional dimension of the heat source.

However, the mechanism of ultrasound's influence on the ARPD temperature characteristics is still unclear. It was suggested that this effect depends on the intensity of ultrasonic waves.

A harmonic symmetric spherical wave in a medium without absorption is given by the equation

$$u(r,t) = \frac{A}{r} \cdot e^{-i\omega t \pm kr}, \qquad (4)$$

where A – the amplitude of ultrasonic oscillations.

The attenuation of ultrasonic oscillations leads to the appearance in the equation of an additional constant multiplier reduced to a unit path length. As a result, for a plane wave propagating along the x-axis, it is possible to write the following

$$I = A_0 \cdot e^{-ax} e^{-ix(t - {}^{x}\!/_{c}\,x)}, \qquad (5)$$

where a – the attenuation coefficient of ultrasonic waves ARPD.

Thus, the intensity of ultrasonic waves, taking into account the attenuation can be estimated as

$$I = \frac{A_1}{r} \cdot e^{-ar}, \qquad (6)$$

where A_1 – reflection coefficient of the medium properties and the parameters of the ultrasonic wave.

Therefore, based on the assumption that the effect of ultrasound depends on the intensity of oscillations at a given point and this dependence is directly proportional, we can write the following equation:

$$\frac{\partial T}{\partial t} = \chi \frac{1}{r} \cdot e^{-ar}, \qquad (7)$$

where χ – reflection coefficient of the medium properties and the parameters of ultrasonic waves on thermal exposure.

Note that in general, the coefficient χ may be different for different amplitude-frequency characteristics of the emitter.

Thus, the change in temperature to a certain extent with ARPD is generally described as a functional correlation:

$$\frac{\partial T}{\partial t}=f\left(\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right],\chi\frac{1}{r}\cdot e^{-ar}\right). \quad (8)$$

Let's represent this dependence using the regression analysis. Perform decomposition in a polynomial:

$$\frac{\partial T}{\partial t}=f\left(\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right],\chi\frac{1}{r}\cdot e^{-ar}\right)\approx$$

$$\approx C_1\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right]+C_2\cdot\chi\frac{1}{r}\cdot e^{-ar}+. \quad (9)$$

$$+C_3\cdot\chi\frac{1}{r}\cdot e^{-ar}\cdot\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right]$$

Applying the condition that in the absence of ultrasound (ie when $\chi = 0$) the equation must be converted into the thermal conductivity equation:

$$\left.\frac{\partial T}{\partial t}\right|_{\chi=0}=C_1\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right]=$$

$$=\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right], \quad (10)$$

thereby, $C_1 = 1$.

Next, we will define the number C_2. Suppose there is an ultrasonic effect, but no thermal effect. It is known that the waves themselves are not sources of heat, so the temperature change should not occur:

$$\left.\frac{\partial T}{\partial t}\right|_{Q=0}=C_2\cdot\chi\frac{1}{r}\cdot e^{-ar}=0.\ . \quad (11)$$

Hence, $C_2 = 0$. Therefore

$$\frac{\partial T}{\partial t}=\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right]+$$

$$+C_3\cdot\chi\frac{1}{r}\cdot e^{-ar}\cdot\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right]=\ . \quad (12)$$

$$=\left(1+C_3\cdot\chi\frac{1}{r}\cdot e^{-ar}\right)\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right]$$

Substituting $C_3\cdot\lambda=\cdot\chi_0$

$$\frac{\partial T}{\partial t}=\left(1+\chi_0\frac{1}{r}e^{-ar}\right)\frac{\lambda}{\rho c_v}\left[\frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)\right]$$

$$\frac{\partial T}{\partial t}=\left(1+\chi_0\frac{1}{r}e^{-ar}\right)\frac{\lambda}{\rho c_v}\left[\frac{2}{r}\cdot\frac{\partial T}{\partial r}\cdot\frac{\partial^2 T}{\partial r^2}\right]. \quad (13)$$

Therefore, the equation for modeling the ultrasonic effect on ARPD is obtained.

Neglecting the effect of convection and diffusion, the time to raise the temperature from T_1 to T_2, we obtain the required time for appropriate heating

$$t=\frac{\rho V\left[c\left(T_2-T_1\right)+\lambda_n\right]}{\eta Q}, \quad (14)$$

V – approximate volume of ARPD;
T_1 – initial temperature ° C;
T_2 – final temperature °C;
ρ – density of ARPD, kg/m^3;
c – heat capacity ARPD, W/K·m^3;
Q – power consumption of the ultrasonic installation, kW;
η – efficiency of the ultrasonic emitter;
λ_n – melting heat of ARPD, kJ/kg.

On the other hand, the time of ultrasonic exposure can be expressed from equation (1) (ignoring the quadratic interaction of time)

$$t=\frac{m_1-0.347-0.126f}{0.204}=4.9m_1-1.7-0.62f\ ,, \quad (15)$$

$$4.9m_1-1.7-0.62f=\frac{m(c(T_2-T_1)+\lambda_n)}{\eta Q}, \quad (16)$$

$$m(c\Delta T+\lambda_n)=\eta Q(4.9m_1-1.7-0.62f), \quad (17)$$

$$mc\Delta T=\eta Q(4.9m_1-1.7-0.62f)-m\lambda_n, \quad (18)$$

$$\Delta T=\frac{\eta Q(4.9m_1-1.7-0.62f)}{mc}-\frac{m\lambda_n}{mc}=$$

$$=\frac{4.9\eta Qm_1}{mc}-\frac{1.7\eta Q}{mc}-\frac{0.62\eta Qf}{mc}-\frac{m\lambda_n}{mc}=$$

$$=\frac{4.9\eta Q}{c}-\frac{1.7\eta Q}{V\cdot\rho\cdot c}-\frac{0.62\eta Qf}{V\cdot\rho\cdot c}-\frac{\lambda_n}{c}= \quad (19)$$

$$=\frac{4.9\eta Q-\lambda_n}{c}-\frac{1.7\eta Q+0.62\eta Qf}{V\cdot\rho\cdot c}$$

Therefore, the predicted temperature difference at which the ARPD will be removed can be determined by the formula

$$\Delta T=\frac{4.9\eta Q-\lambda_n}{c}-\frac{1.7\eta Q+0.62\eta Qf}{V\cdot\rho\cdot c}. \quad (20)$$

Conclusions

Experimental studies of the ultrasonic influence mechanism on the solid's surface suggest the possibility of using the ultrasonic method to countermeasure ARPD.

Experimental studies were planned according to the method of experiment planning, which reduced the volume of studies to nine experiments (with three iterations at each point of the experiment), while not reducing the reliability of the results and the correlation adequacy. The obtained equations for determining the quantity of removed ARPD depending on the time and frequency of ultrasonic interaction enable predicting the time required to get rid of ARPD on the pipe surface. The results' probability of exceedance is R=0.975.

After analyzing the obtained graphs and correlations, it was determined that the time of ultrasonic interaction has the greatest influence on the mass of removed ARPDs because in the response surface equation the coefficient is the largest and positive.

The proposed algorithm for finding the ultrasonic treatment optimal operational parameters can also be used in the run-in hole ultrasonic equipment's operating parameters selection in certain field conditions.

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