RESEARCHES OF THE ELECTRODYNAMIC CHARACTERISTICS OF OILY SUBSTANCES IN THE MICROWAVE RANGE

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Igor V. Bogachkov,
Omsk State Technical University (OmSTU), Omsk, Russia,
bogachkov@mail.ru

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Results of researches of the electromagnetic properties of oil substances in the microwave frequency band are presented in this work. Possibilities of using microwave heating in oil industry and pumping of oil products are considered. The possibility of using microwave heating to solve a number of problems of oil production and pumping oil through pipelines is being researched. Using waves in the microwave range allows in many cases to concentrate the heat release in the most viscous paraffin and bitumen components, which as a result reduces the viscosity of these components. To determine optimal wave frequencies and powers used for heating, it is necessary to know the electromagnetic characteristics of oil-containing mixtures. Experimental researches consisted in measuring the attenuation of electromagnetic waves passing through a "clean" section of the waveguide and through the same section of the waveguide after passing petroleum products of various compositions through it.The additional attenuation of oil pollutions in the frequency band 9-11 GHz does not exceed 0.27 dB/m. To determine the electromagnetic properties of oil-containing materials in the microwave band, experimental researches were conducted on the coaxial segment, which is filled with the researching substance. Losses in conductors are dominated by losses in contact connections. The wave penetration depth in the substance decreases with an increase in frequency, which must be taken into account in the heating technology. Parameters of researching substances were calculated, and their frequency dependences are presented. The losses in oil deposits significantly exceed losses in pure oil, therefore these deposits will heat up more, than pure oil. This effect can be used to reduce the viscosity of oil both in oil pipelines during oil transportation and in the production of high viscosity oil. It is possible to determine the required heating power and time to use microwave heating technology for the oil industry.

Information about author:

Igor V. Bogachkov, *Professor of "Communication means and information security" department of Omsk State Tech-nical University (OmSTU), Adv. Dr., Docent, Senior Member IEEE, Omsk, Russia*

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Introduction

Currently, the possibility of using microwave heating to solve a number of problems of oil production (extraction of high-viscosity oil, dewaxing of wells) and pumping oil through pipelines is being researched [1-11].

The use of electromagnetic waves in the microwave range (from 0.3 to 30 GHz – UHF (ultra-high frequencies – 0.3 GHz to 3 GHz) and SHF (super-high frequencies – 3 GHz to 30 GHz)) allows in many cases to concentrate the heat release in the most viscous paraffin and bitumen components, thereby heating them, which as a result reduces the viscosity of these components improves the homogeneity of the produced oil mixture [4, 7-9].

One of the important areas of application of microwave heating may be the repair and maintenance of oil wells, solving problems associated with the formation of bitumen-paraffin plugs and high oil viscosity [4, 7-12, 20-24].

The pipes of standard diameters used to solve the above problems are natural waveguides of electromagnetic waves, which form equivalent guide systems of the microwave range (a circular waveguide or a coaxial line).

The optimal operating frequencies of these guiding systems, taking into account their equivalent loads, will be in the microwave range. As is known, the heating efficiency due to the absorption of electromagnetic waves increases with increasing frequency [4-6].

According to experts [1-9], the model for pipes of an oil well in the form of a coaxial line does not always adequately describe the system. Of particular interest is the study of waveguide mode types [5, 16], which for pipe diameters used in wells will have optimal frequencies in the microwave range.

The decision on the technical feasibility and economic efficiency of a heater based on electromagnetic waves requires the study of a number of issues (for example, the study of the effect of oil residues on the walls of a pumping and compressor system used in a corresponding installation as a waveguide) [10-15]. According to its electromagnetic properties, a paraffin plug can be considered an ordinary load of the microwave tract, which will be heated by absorbing the energy of electromagnetic waves.

The heating efficiency of such a load is reduced due to losses in the waveguide, therefore it is necessary to study the effect of the oil film that remains on the walls of the waveguide [4, 10-12].

To determine the optimal frequencies and powers of electromagnetic waves used for heating, it is necessary to know the electromagnetic characteristics of oil-containing mixtures (ε is a relative permittivity (relative dielectric constant) of filling, tg δ – tangent of the dielectric loss angle, etc.).

Some electrodynamic parameters of oil and oil-containing materials are given in the works [1-3], but researches were limited to the high frequency range, and only in [6] researches of parameters in the frequency range up to 1 GHz were given.

When filling an empty segment of the transmission line with a substance, both the SWR (standing wave ratio) and attenuation will change. From this information, it is possible to determine the electrodynamic characteristics of the filling: ε, tgδ, etc.

$$\tilde{\varepsilon} = \varepsilon' - i\varepsilon'' = \varepsilon\left(1 - i\,\mathrm{tg}\,\delta\right) = \varepsilon\sqrt{1+(\mathrm{tg}\,\delta)^2}\,\exp\left(-i\delta\right), \quad (1)$$

where $\tilde{\varepsilon}$ is a complex relative permittivity, $\varepsilon^{/}$ is a real part of $\tilde{\varepsilon}$: $\varepsilon^{/} = \varepsilon$), $\varepsilon^{//}$ is an imaginary part associated with losses in the dielectric), i is an "imaginary unit".

Experimental setup and content of the experiment with a measuring segment based on a single-connected rectangular waveguide

Since in a real design in the form of a circular metal tube, the propagation of the H_{11} wave is assumed (the mode of the main type, although the excitation of the H_{01} mode is of particular interest, which would reduce the attenuation of electromagnetic waves during propagation [5, 16]), a segment of a rectangular waveguide with the cross section 23×10 mm was taken for the experiment, in which the mode of the main type (H_{10}) was excited.

The length of the waveguide segment (l) is 750 mm.

The choice of such a waveguide is due to the ease of connection to existing equipment and the fact that the spatial structures of the corresponding electromagnetic waves are equivalent, which means that the losses in the walls of the waveguides will be approximately equal [5, 16].

Experimental researches consisted in measuring the attenuation of electromagnetic waves that passed through the "clean" section of the waveguide (without petroleum substances on the walls) and through the same section of the waveguide after passing oil of various compositions through it.

A panoramic SWR meter P2-54/3 was used to measure attenuation of electromagnetic waves. The measurements were carried out in the operating frequency band of the selected waveguide (from 9 to 11 GHz). The scheme of the measuring set is shown in Figure 1, where D_1 and D_2 are detector heads, DC_1 and DC_2 are directional couplers.

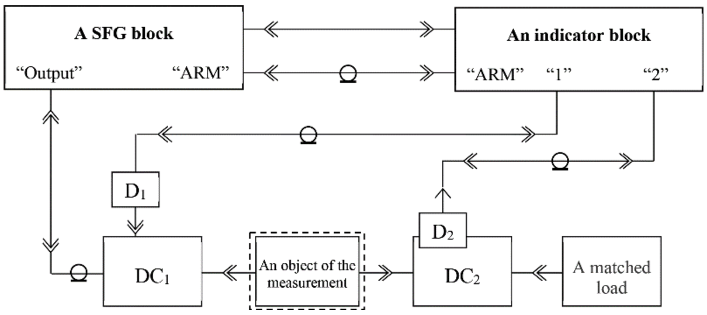

Fig. 1. The scheme of the experiment

After calibration of the measuring equipment, attenuation was measured in the "clean" waveguide section (without petroleum substances on the walls) – "An object of the measurement" in Figure 1.

Then oil was passed through the same section of the waveguide. When the oil stopped dripping from the ends of the measured waveguide section, it was connected to the path of the measuring device, and the attenuation is measured again.

Analysis of the results of an experiment with a waveguide segment

The attenuation for a "clean" section of the waveguide in the frequency band under consideration was 0.25 dB on average, and for a contaminated waveguide in the frequency band from 9 GHz to 11 GHz, the attenuation averaged 0.45 dB. As follows from the data obtained, the additional attenuation due to oil pollution for the measured waveguide segment does not exceed 0.2 dB and almost does not change in the specified frequency range.

Assuming that the total attenuation of the electromagnetic wave in this case is exponential, and the attenuation indicators (in dB) caused by individual factors add up, we obtain that, according to the measurement results, the additional attenuation due to oil pollution is approximately $\alpha = 0.27$ dB/m.

Experimental setup and content of the experiment with a measuring segment based on a coaxial line

To determine the electromagnetic properties of oil and liquid oil-containing materials (oil deposits in wells, pipelines, etc.) in the frequency range from 2 to 18 GHz, experimental studies of the coaxial line segment, which has a disassembled structure and is completely filled with the substance under researches, were carried out (Fig. 2).

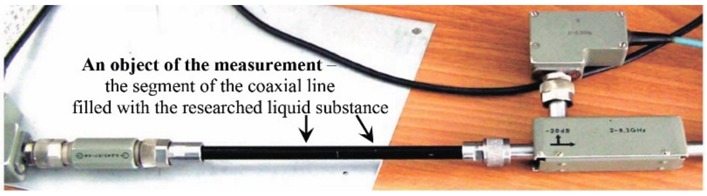

Fig. 2. The object of the measurement

The length of the segment (l) is 9 cm, the diameter of the inner conductor is 3 mm, and the diameter of the outer conductor is 7 mm.

The characteristic resistance (Z_c) of an unfilled measured coaxial segment, as well as connecting segments of coaxial lines, is 50 Ohm. The dimensions of this segment are selected so that a single-mode mode is provided in the line [5].

Figure 3 shows the scheme of the experimental setup.

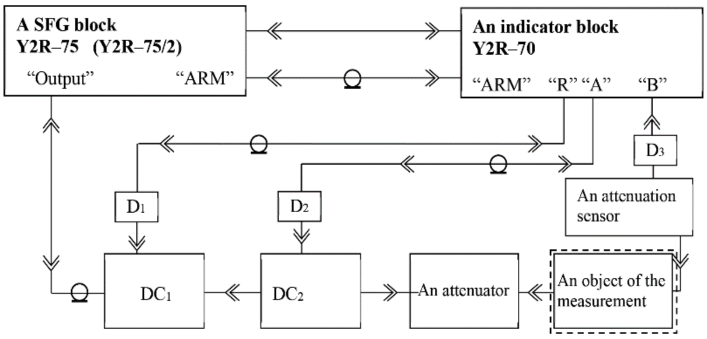

Fig. 3. A scheme of the experimental set with VSWR measuring instrument R2-103 (R2-104)

The experimental scheme, measurement technique, and calculation method of electrodynamics parameters are described in detail in [17].

After calibration, the measuring object was connected to the system, and its frequency characteristics of VSWR (voltage standing wave coefficient) at the input and attenuation (A, dB) at the output were measured.

The instrument measurement errors are as follows: $\Delta SWR(\%) = 5 \cdot SWR_m$, $\Delta A(\text{dB}) = \pm(0.04A_m + 0.3)$, $\Delta f(\%) = 0.5 f_m$, where f is the frequency, and the "m" indexes correspond to the measured values [18, 19].

Experimental studies of the coaxial segment in the frequency range from 2 GHz to 8.5 GHz

For measurements in the frequency range from 2 to 8.5 GHz, the panoramic VSWR and attenuation meter (A, dB) P2-103 was used [17, 18].

Figure 4 shows a photo of the VSWR meter screen for the frequency range from 2 GHz to 8.5 GHz when filling the segment with oil deposits.

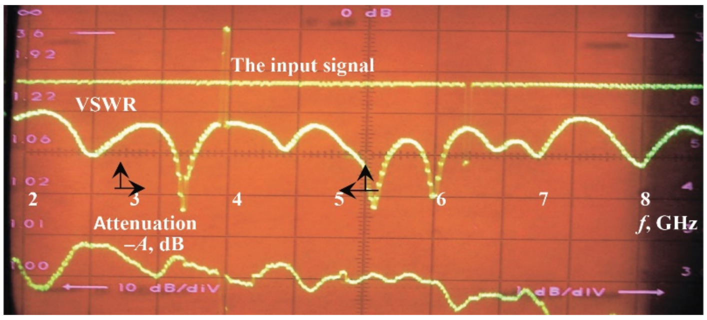

Fig. 4. Photo of the meter screen (P2-103) for the coaxial segment filled with oil deposits

The frequency dependences of the VSWR (f) obtained during experimental measurements are presented below (in Fig. 5) and A, dB (f) (in Fig. 6).

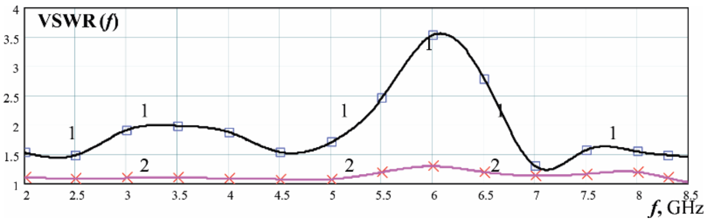

Fig. 5. VSWR (f) when filled with oil ("1") and without filling ("2")

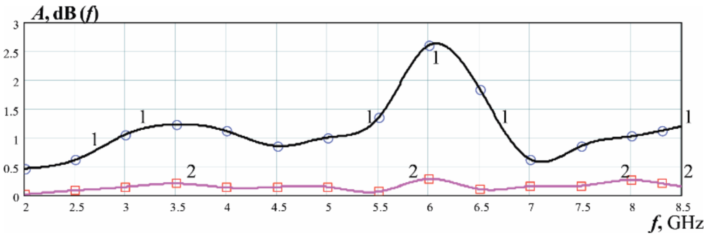

Fig. 6. Frequency response A (dB) when filled with oil ("1") and without filling ("2")

In addition to the data for the segment filled with oil ("1"), graphs for the unfilled segment ("2") are also given. The experimental data are connected by an interpolation curve for convenience.

Figures 7 and 8, respectively, show similar dependencies (frequency characteristics of VSWR (f) and attenuation (A, dB (f)) for a segment filled with oil deposits taken from an oil pipeline.

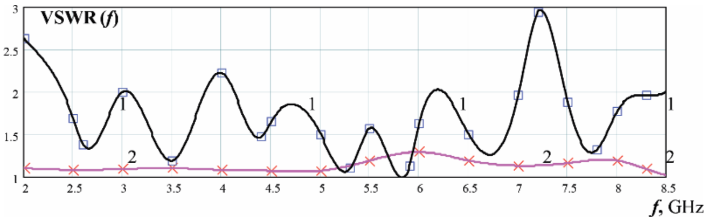

Fig. 7. VSWR (f) when filling the segment with oil deposits (“1”) and without filling (“2”)

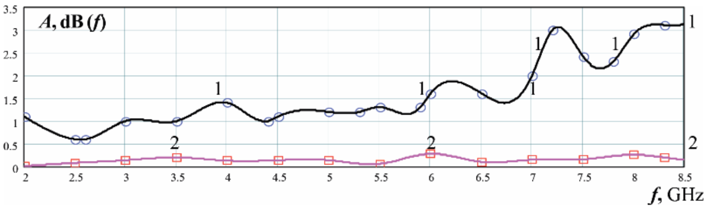

Fig. 8. Frequency response A (dB) when filling the segment with oil deposits (“1”) and without filling (“2”)

Experimental studies of the coaxial segment in the frequency range from 8 GHz to 18 GHz

For measurements in the frequency range from 8 GHz to 18 GHz, the panoramic VSWR and attenuation meter (*A*, dB) P2-104 was used [17, 19].

Figure 9 shows a photo of the VSWR meter screen when filling the segment with oil deposits.

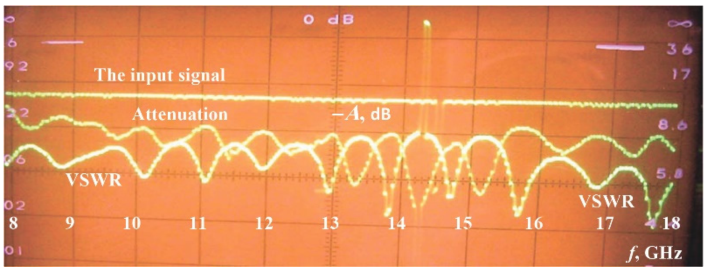

Fig. 9. Photo of the meter screen (P2-104) for a coaxial segment filled with oil deposits

Figure 10 shows the data obtained from experimental measurements of VSWR (*f*), and Figure 11 presents the dependence of *A*, dB (*f*).

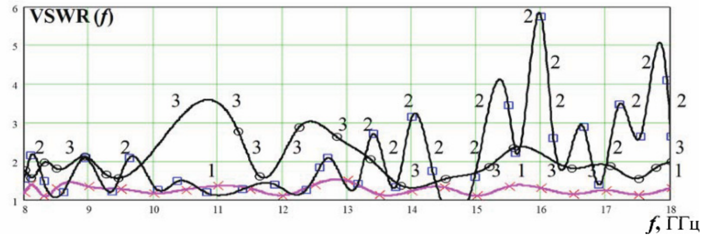

Fig. 10. VSWR (f) dependence when filling coaxial segment with oil (“2”), oil deposits (“3”) and without filling (“1”)

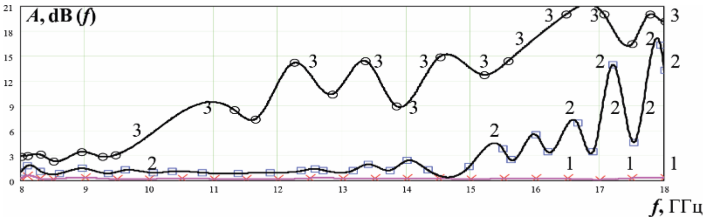

Fig. 11. Frequency response A (dB) when filling coaxial segment with oil (“2”), oil deposits (“3”) and without filling (“1”)

In addition to the data for the filled segment with oil (“2”) and oil deposits (“3”), graphs for the unfilled segment (“1") are also shown”).

The experimental data are connected by an interpolation curve for convenience.

A calculation of electromagnetic characteristics of the researched substances

As is known, even at low frequency, oil is a dielectric (conductivity is practically zero), therefore, the microwave frequency range, absorption losses in oil are determined only by polarization effects (the full angle tangent of the dielectric loss (tg δ) is determined only by the angle tangent of the polarization loss). In the future, we will assume that the magnetic properties of oil can be neglected (the relative magnetic permeability is “1”), and the total losses in the studied substances will be insignificant (tg$\delta < 0.2$) [17-20].

To obtain quantitative characteristics, it is convenient to use the models and techniques presented in [17].

At the entrance of the measuring object, after filling it with the test substance, there is a boundary between the media (a jump in characteristic resistance from Z_c to $Z_c\sqrt{\varepsilon}$). At the output of the measuring object there will be a reverse jump (from $Z_c\sqrt{\varepsilon}$ to Z_c), which gives modulo the same reflection coefficient (R) as at the input, but with the opposite sign.

The total reflection coefficient at the input (R_{in}) is determined by the superposition of waves reflected from the input and output, taking into account the phase shift (βl).

The scattering matrix (S-matrix) of the filled measurement object, taking into account losses, is determined by the formula:

$$S = \begin{bmatrix} R & Te^{-\gamma l} \\ Te^{-\gamma l} & -Re^{-2\gamma l} \end{bmatrix}, \tag{2}$$

where $T = \sqrt{1-R^2} = \dfrac{2\sqrt[4]{\tilde{\varepsilon}}}{1+\sqrt{\tilde{\varepsilon}}}$ is the transmission coefficient according to the reduced voltage [16, 17], γ(longitudinal wave propagation coefficient) = $\alpha + i\beta$, where α and β are the attenuation and phase coefficients respectively, and R is calculated using the following formula [17]:

$$R = \left| \frac{Z_c/\sqrt{\tilde{\varepsilon}} - Z_c}{Z_c/\sqrt{\tilde{\varepsilon}} + Z_c} \right| = \left| \frac{1-\sqrt{\tilde{\varepsilon}}}{1+\sqrt{\tilde{\varepsilon}}} \right| = \left| \frac{1-\sqrt{\varepsilon\sqrt{1+(\mathrm{tg}\,\delta)^2}\ \mathrm{e}^{-i\delta/2}}}{1+\sqrt{\varepsilon\sqrt{1+(\mathrm{tg}\,\delta)^2}\ \mathrm{e}^{-i\delta/2}}} \right|, \tag{3}$$

If the loss of the substance filling the measuring object is small ($\mathrm{tg}\,\delta \ll 1$), then α and β are calculated using the following formulas (4) (c is the speed of light in the vacuum):

$$\alpha \approx \frac{\pi f \sqrt{\varepsilon}}{c} \operatorname{tg}\delta, \ \beta \approx \frac{2\pi f \sqrt{\varepsilon}}{c}\left(1+\frac{(\operatorname{tg}\delta)^2}{8}\right). \quad (4)$$

Using the D-matrix method [16, 17, 21], we can obtain the reflection coefficient at the input (R_{in}) and the transmission coefficient at the output of the measurement object (T_{out}):

$$R_{in} = \frac{R - R(R^2+T^2)e^{-2\gamma l}}{1-R^2 e^{-2\gamma l}} = \frac{R(1-e^{-2\gamma l})}{1-R^2 e^{-2\gamma l}}, \quad (5)$$

$$T_{out} = \frac{T^2 e^{-\gamma l}}{1-R^2 e^{-2\gamma l}} = \frac{(1-R^2)e^{-\gamma l}}{1-R^2 e^{-2\gamma}}. \quad (6)$$

After measuring the SWR, it is possible to determine the R_{in}:

$$R_{in} = \frac{\mathrm{SWR}-1}{\mathrm{SWR}+1}, \quad (7)$$

The analysis of formula (5) shows that the frequency dependence of R_{in} at low R and low losses (α) has a pronounced periodicity.

$$R_{in} \approx R(1-e^{-2\gamma l}) \to 1-e^{-2i\beta l}. \quad (8)$$

Minimums will be observed at $\beta l = \pi n$ (n is a natural number):

$$f_{\min} = \frac{cn}{2l\sqrt{\varepsilon\left(1+0.25(\operatorname{tg}\delta)^2\right)}}. \quad (9)$$

The maximums will be observed at $\beta l = \pi(n+0.5)$:

$$f_{\max} = \frac{c(n+0.5)}{2l\sqrt{\varepsilon\left(1+0.25(\operatorname{tg}\delta)^2\right)}}. \quad (10)$$

After calculating the distances between two maxima or minima, it is possible to express the necessary parameters for a certain frequency range ($f_{\mathrm{n}} \ldots f_{\mathrm{n+1}}$) [17, 21, 22]:

$$\varepsilon\left(1+0.25(\operatorname{tg}\delta)^2\right) = \frac{c^2}{4l^2\left(f_{\mathrm{n+1}}-f_{\mathrm{n}}\right)^2}. \quad (11)$$

After processing the experimental results, the frequency dependences $|R_0|$ and $|T_0|$ (index "0" corresponds to the values for the "clean" segment) are determined for the "clean" (without filling with matter) section. This allows us to identify the systematic error of the experiment and correct the result ($R(f)$ and A(dB) (f)) for the filled segment [17].

The attenuation coefficient in the filling substance (α_d) is obtained from the analysis of relative capacities (P_d is the power of absorption losses in the filling substance, P_{ref} is the power of the reflected wave, P_l is the power of the wave that passed through the load).

$$P_d + P_0 = 1 - P_{ref} - P_l = 1 - |R_{in}|^2 - |T_{out}|^2. \quad (12)$$

After the transformations, the formula is obtained:

$$\alpha_d = \frac{1}{l}\left[\ln\left(\sqrt{1-|R_{in}|^2}\right) - \ln|T_{out}|\right] - \alpha_0 =$$
$$\left[\ln\left(\sqrt{1-|R_{in}|^2}\right) - \ln|T_{out}| - \ln\left(\sqrt{1-|R_0|^2}\right) + \ln|T_0|\right]/l. \quad (13)$$

The analysis showed that in the unfilled segment, losses in the contact connections prevail over losses in the conductors.

After calculating α_d by the formula (4), the value is calculated $\sqrt{\varepsilon}\operatorname{tg}\delta$.

Solving equations (3-13) together, it is possible to calculate the necessary parameters of the substance filling the segment (ε and tgδ), and then (if necessary) – and $\tilde{\varepsilon}$, ε^{l}, ε^{ll} using formulas (1) [17].

Analysis of the results of experimental studies

After processing the experimental results according to the method described above, the electromagnetic parameters of the substances under study were calculated and their frequency dependences are presented.

Figure 12 shows graphs of the frequency characteristics of the loss coefficients in the filling of the coaxial segment.

As the analysis of graphs shows, losses in oil deposits at $f > 5$ GHz significantly exceed losses in pure oil (Fig. 12), therefore, these deposits will heat up more than pure oil. This effect can be used to reduce the viscosity of oil both in the oil pipeline during oil transportation and in the production of high viscosity oil [4].

The power of heat loss (P) in the volume of the substance (V) is determined by the following formula:

$$P/V = 2\pi f \varepsilon\varepsilon_0 \operatorname{tg}\delta E^2 \text{ or}$$
$$P/V = 556\varepsilon'' f[\mathrm{GHz}]\cdot\left(E[\mathrm{V/cm}]\right)^2, \quad (14)$$

where E is the voltage of the electrical component of the electromagnetic field, and ε_0 is the dielectric constant.

Figure 13 shows graphs of frequency dependences of the absorption coefficient (εtgδ), which is directly proportional to the power absorbed in the substance in a typical microwave heating model.

As the analysis shows, losses in oil deposits in the studied frequency range significantly exceed losses in pure oil, therefore these deposits will heat up more than pure oil (Fig. 12 and 13).

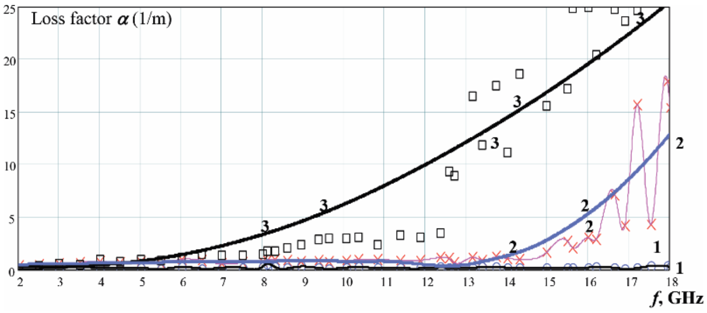

Fig. 12. Graph of the frequency dependence of the loss coefficient: 1 – in the clean segment, 2 – oil filling, 3 – when filling with oil deposits

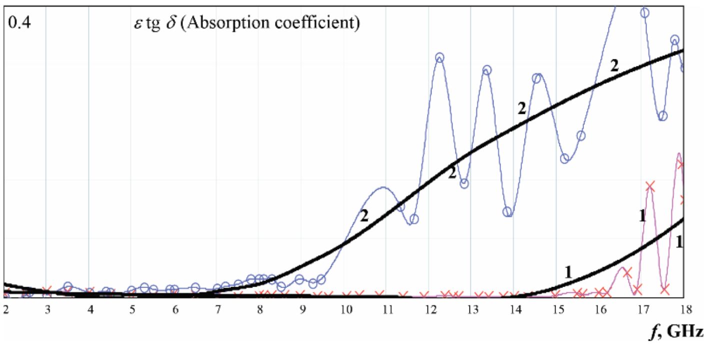

Fig. 13. Graph of the frequency dependence of the absorption coefficient: 1 – for oil filling, 2 – for filling with oil deposits

This effect can be used to reduce the viscosity of oil in an oil pipeline during oil transportation, which will eventually reduce deposits on the walls of the pipeline.

The depth of penetration of the electromagnetic wave into the substance decreases with increasing frequency $\left(1/\alpha = \dfrac{c}{\pi f \sqrt{\varepsilon} \, \mathrm{tg}\delta}\right)$, which must be taken into account in microwave heating technology.

Frequency characteristics for many other characteristics of oil and oily substances are presented in works [18-20].

Conclusions

The level of losses in oil deposits turns out to be sufficient for the implementation of microwave heating.

If the mixture contains water, it will increase the losses in the substance and improve the conditions for microwave heating.

The research results make it possible to optimize microwave heating technologies in the oil industry, etc.

To determine the characteristics of the electromagnetic wave generator of the installation (required pulsed or continuous power, operating frequencies, operating modes, etc.), it is necessary to obtain electromagnetic characteristics of samples from real bitumen-paraffin plugs and other oily substances [20-24].

With known electromagnetic wave parameters, it is possible to determine the required heating power, develop microwave heating technology, and determine the area of the predominant electromagnetic wave concentration in the substance, which is associated with the depth of penetration of the electromagnetic wave into the substance.

The depth of the electromagnetic wave penetration into the substance decreases with increasing frequency, which must be taken into account in microwave heating technology.

References

1. *Morozov N.N., Kashkatenko G.V.* Microwave heating of petroleum products in pipelines // Bulletin of MSTU, 2010. Vol. 13. No. 4/2, pp. 974-976.

2. *Fitzner A.F.* Existing methods of microwave energy application in oil and gas industry // Bulletin of Science and Education, 2018. No. 11(47), pp. 13-16.

3. *Gyulmaliyev E.A., Tretyakov V.F., Talyshinsky R.M., Borisov V.P., Movsumzade E.M.* Chemical aspects of the technology development of microwave frequency. Opportunities and prospects of using microwave radiation // History and pedagogy of natural sciences, 2015. No. 2, pp. 59-68.

4. News of universities. Oil and gas. Tyumen: Publishing House of Tyumen State Technical University, 2021-2023.

5. *Bogachkov I.V.* Microwave devices. Microwave guiding media // Omsk, OmSTU publishing house, 2022. 120 p.

6. *Kitsis S.I.* On the optimal frequency of HF heating of the bottom-hole zone of an oil well // News of universities. Oil and Gas, 2001. No. 2, pp. 50-57.

7. *Leontyev A.Yu., Poletaeva O.Yu., Babaev E.R., P.Sh. Mamedova* Application of microwave irradiation on extra-heavy crude oil // Oil & Gas Cheymistry, 2019. No. 2, pp. 13-17.

8. *Leontyev A.Yu., Poletaeva O.Yu., Babaev E.R., Mamedova P.Sh.* Influence of microwave exposure on the change of the viscosity of highly viscous heavy oil // Oil & Gas Cheymistry, 2018. No. 2, pp. 25-27.

9. *Sekachyov A.F., Shalay V.V., R.N. Ivanov V.V. et al.* Analysis of the efficiency of energy transfer to oil media // Territory of Neftegaz, 2021. No. 9-10, pp. 74-79.

10. *Kovaleva L.A., Zinnatullin R.R., Valeev M.D. et al.* Laboratory studies of heating of high-viscosity oils in pipelines by a high-frequency electromagnetic field // Oil industry, 2019. No. 2, pp. 82-85.

11. *Morozov N.N.* Development of microwave technology for pipeline protection against blockages during transportation of viscous liquids // Bulletin of MSTU, 2013. Vol. 16. No. 1, pp. 135-136.

12. Patent No. 2681619 Russia (OmSTU). Method and device for liquefying oil sludge inside reservoirs and closed containers with a microwave field / *V.P. Kismereshkin, A.F. Sekachev, A.E. Yakovlev, A.F. Fitzner*. 2017147175. announced on 29.12.2017. published on 11.03.2019.

13. *Kovaleva L.A., Zinnatullin R.R., Mullayanov A.I. et al.* Evolution of the microstructure of oil-water emulsions in high-frequency and ultra-high-frequency electromagnetic fields // Thermophysics of high temperatures, 2013. Vol. 51. No. 6, pp. 952-955.

14. *Dolomatov M.Y., Sabitov R.S., Safuanova R.M., Telin A.G.* On the destruction of hydrocarbon emulsions under the action of electromagnetic fields // Problems of collection, preparation and transport of oil and petroleum products, 2017. No. 2 (108), pp. 39-51.

15. *Sekachev A.F., Shalai V.V., Zemenkov Yu.D. et al.* Experimental study of the transmission of energy of an ultrahigh-frequency electromagnetic field into an oil medium by means of an immersion radiator // Oil industry, 2021. No. 3, pp. 120-129.

16. *Bogachkov I.V.* Microwave devices. Matrix methods of analysis of microwave devices // Omsk, OmSTU publishing house, 2022. 116 p.

17. *Bogachkov I.V.* Determination of electromagnetic parameters of liquid substances in the microwave range // T-Comm, 2024. Vol. 18. No. 5.

18. *Maistrenko V.A., Bogachkov I.V., Yeletsky A.I., Katunsky E.A.* Experimental researches of electromagnetic properties of oil and oil deposits in the range 2-8.5 GHz // Omsk scientific bulletin, 2006. No. 1 (34), pp. 95-101.

19. *Maistrenko V.A., Bogachkov I.V., Yeletsky A.I., Katunsky E.A.* Experimental researches of electromagnetic properties of oil and oil deposits in the range of 8-18 GHz // Omsk scientific bulletin, 2006. No. 2 (35), pp. 148-150.

20. *Paradeev V.D., Maistrenko V.A., Bogachkov I.V., Yeletsky A.I.* Application of electromagnetic radiation of the microwave range of high power in the oil industry // Territory of Neftegaz, 2006. No. 4, pp. 48-49.

21. *Bogachkov I.V.* Constructing of multichannel waveguide energy distribution systems for the microwave heating based on T-junctions with elongated shoulders with minimal input mismatch // T-Comm, 2024. Vol. 18. No. 2, pp. 51-57.

22. *Bogachkov I.V.* Research of methods to improve the distributing of electromagnetic field in the heating chamber of microwave ovens // T-Comm, 2024. Vol. 18. No. 4.

23. *Izmailova G.R.* Simulation of electromagnetic-acoustic heating of the oil layer in laboratory conditions // Siberian Journal of Physics, 2021. Vol. 16. No. 1, pp. 109-116.

24. *Shagiev R.G.* Analysis of oil heating in pipelines using drag reducing agents // Problems of collecting, preparing and transporting oil and petroleum products, 2021. Vol. 1 (129), pp. 79-91.

ИЗУЧЕНИЕ ЭЛЕКТРОДИНАМИЧЕСКИХ ХАРАКТЕРИСТИК НЕФТЕСОДЕРЖАЩИХ ВЕЩЕСТВ В МИКРОВОЛНОВОМ ДИАПАЗОНЕ

Богачков Игорь Викторович, *Омский государственный технический университет (ОмГТУ), г. Омск, Россия,* **bogachkov@mail.ru**

Аннотация

В этой работе приведены результаты экспериментальных исследований электромагнитных свойств нефти и нефтяных отложений в микроволновом диапазоне частот, рассмотрены возможности применения микроволнового нагрева при нефтедобыче и при перекачках нефти и нефтепродуктов. Изучается возможность применения микроволнового нагрева к решению ряда проблем нефтедобычи, перекачки нефти по трубопроводам. Применение электромагнитных волн микроволнового диапазона позволяет во многих случаях сконцентрировать выделение тепла в более вязких парафиновых и битумных компонентах, что в результате уменьшит вязкость этих компонент. Для определения оптимальных параметров электромагнитных волн, используемых для нагрева, необходимо знать электромагнитные характеристики нефтесодержащих смесей таких, как относительная диэлектрическая проницаемость заполнения, тангенс угла диэлектрических потерь. Экспериментальные исследования заключались в измерении затухания волн, прошедшей через "чистый" отрезок волновода и через тот же отрезок волновода после пропускания через него нефтепродуктов различного состава. Как следует из полученных данных, дополнительное затухание в полосе рабочих частот 9-11 ГГц за счет нефтяного загрязнения для измеренного отрезка волновода не превышает 0.27 дБ/м. Для определения электромагнитных свойств нефтесодержащих материалов были проведены экспериментальные исследования отрезка коаксиальной линии, который имеет разбираемую конструкцию и полностью заполняется исследуемым веществом. В незаполненном отрезке преобладают потери в контактных соединениях. Глубина проникновения волн уменьшается с ростом частоты, что необходимо учитывать в технологии нагрева. Представлены параметры исследуемых веществ и построены их частотные зависимости. Потери в нефтяных отложениях превышают потери в чистой нефти, поэтому эти отложения будут нагреваться сильнее, чем чистая нефть. Этот эффект можно использовать для снижения вязкости нефти как в нефтепроводе при транспортировке нефти, так и при добыче нефти повышенной вязкости. При известных их характеристиках можно определить необходимую мощность нагрева и разработать технологию микроволнового нагрева для нефтедобывающей промышленности.

Ключевые слова: *микроволновый нагрев, нефтесодержащие вещества, коэффициент отражения, коэффициент потерь, микроволновый диапазон, метод D-матриц.*

Литература

1. *Морозов Н.Н., Кашкатенко Г.В.* Микроволновый разогрев нефтепродуктов в трубопроводах // Вестник МГТУ, 2010. Т. 13. № 4/2. С. 974-976.
2. *Фицнер А.Ф.* Существующие способы применения микроволновой энергии в нефтегазовом деле // Вестник науки и образования, 2018. № 11(47). С. 13-16.
3. *Гюльмалиев Э.А., Третьяков В.Ф., Талышинский Р.М., Борисов В.П., Мовсумзаде Э.М.* Химические аспекты развития технологии СВЧ. Возможности и перспективы использования микроволнового излучения // История и педагогика естествознания, 2015. № 2. С. 59-68.
4. Известия вузов. Нефть и газ. Тюмень: Изд-во ТюмГНТУ, 2021-2023.
5. *Богачков И.В.* Устройства СВЧ. Направляющие среды УВЧ и СВЧ. Омск: Изд-во ОмГТУ, 2022. 120 с.
6. *Кицис С.И.* К оптимальной частоте ВЧ нагрева призабойной зоны нефтяной скважины // Известия вузов. Нефть и газ, 2001. № 2. С. 50-57.
7. *Леонтьев А.Ю., Полетаева О.Ю., Бабаев Э.Р., Мамедова П.Ш.* Применение СВЧ-воздействия на высоковязкую тяжелую нефть // НефтеГазоХимия, 2019. № 2. С. 13-16.
8. *Леонтьев А.Ю., Полетаева О.Ю., Бабаев Э.Р., Мамедова П.Ш.* Влияние СВЧ-воздействия на изменение вязкости высоковязких тяжелых нефтей // НефтеГазоХимия, 2018. № 2. С. 25-27.
9. *Секачёв А.Ф., Шалай В.В., Иванов Р.Н.* и др. Анализ эффективности передачи в нефтяные среды энергии // Территория Нефтегаз, 2021. № 9-10. С. 74-79.
10. *Ковалева Л.А., Зиннатуллин Р.Р., Валеев М.Д.* и др. Лабораторные исследования нагрева высоковязких нефтей в трубопроводах высокочастотным электромагнитным полем // Нефтяное хозяйство, 2019. № 2. С. 82-85.
11. *Морозов Н.Н.* Разработка СВЧ-технологии защиты трубопровода от закупорок при транспортировке вязких жидкостей // Вестник МГТУ, 2013. Т. 16. № 1. С. 135-136.
12. Патент № 2681619. Способ и устройство разжижения нефтяных шламов внутри резервуаров и закрытых емкостей СВЧ-полем / В.П. Кисмерешкин, А.Ф. Секачёв, А.Е. Яковлев, А.Ф. Фицнер (ОмГТУ, Российская Федерация). № 2017147175. - заявл. 29.12.2017. опубл. 11.03.2019.
13. *Ковалева Л.А., Зиннатуллин Р.Р., Муллаянов А.И.* и др. Эволюция микроструктуры водонефтяных эмульсий в высокочастотных и сверхвысокочастотных электромагнитных полях // Теплофизика высоких температур, 2013. Т. 51. № 6. С. 952-955.

14. *Доломатов М.Ю., Сабитов Р.С., Сафуанова Р.М., Телин А.Г.* О разрушении углеводородных эмульсий под действием электромагнитных полей // Проблемы сбора, подготовки и транспорта нефти и нефтепродуктов, 2017. № 2 (108). С. 39-51.
15. *Секачёв А.Ф., Шалай В.В., Земенков Ю.Д.* и др. Экспериментальное исследование передачи энергии сверхвысокочастотного электромагнитного поля в нефтяную среду посредством погружного излучателя // Нефтяное хозяйство, 2021. № 3. С. 120-129.
16. *Богачков И.В.* Устройства СВЧ. Матричные методы анализа СВЧ-устройств. Омск: Изд-во ОмГТУ, 2022. 116 с.
17. *Bogachkov I.V.* Determination of electromagnetic parameters of liquid substances in the microwave range // T-Comm: Телекоммуникации и транспорт, 2024. Т. 18. № 5.
18. *Майстренко В.А., Богачков И.В., Елецкий А.И., Катунский Е.А.* Экспериментальные исследования электромагнитных свойств нефти и нефтяных отложений в диапазоне 2-8,5 ГГц // Омский научный вестник, 2006. № 1 (34). С. 95-101.
19. *Майстренко В.А., Богачков И.В., Елецкий А.И., Катунский Е.А.* Экспериментальные исследования электромагнитных свойств нефти и нефтяных отложений в диапазоне 8-18 ГГц // Омский научный вестник, 2006. № 2 (35). С. 148-150.
20. *Парадеев В.Д., Майстренко В.А., Богачков И.В., Елецкий А.И.* Применение электромагнитного излучения микроволнового диапазона большой мощности в нефтедобывающей промышленности // Территория Нефтегаз, 2006. № 4. С. 48-49.
21. *Bogachkov I.V.* Constructing of multichannel waveguide energy distribution systems for the microwave heating based on T-junctions with elongated shoulders with minimal input mismatch // T-Comm: Телекоммуникации и транспорт, 2024. Т. 18. № 2. С. 51-57.
22. *Bogachkov I.V.* Research of methods to improve the distributing of electromagnetic field in the heating cham-ber of microwave ovens // T-Comm: Телекоммуникации и транспорт, 2024. Т. 18. С. 4.
23. *Измайлова Г.Р.* Имитация электромагнитно-акустического нагрева нефтяного пласта в лабораторных условиях // Сибирский физический журнал. 2021. Т. 16. № 1. С. 109-116.
24. *Шагиев Р.Г.* Анализ нагрева нефти в трубопроводах с применением противотурбулентных присадок // Проблемы сбора, подготовки и транспорта нефти и нефтепродуктов, 2021. Т. 1 (129). С. 79-91.

Информация об авторе:
Богачков Игорь Викторович, *доктор технических наук, доцент; профессор кафедры "Средства связи и информационная безопасность" Омского государственного технического университета (ОмГТУ), Senior Member IEEE, г. Омск, Россия*