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# Investigation of Source Rock Heating and Structural Changes in the Electromagnetic Fields Using Experimental and Mathematical Modeling

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Abstract: The paper presents the results of an experimental study of heating and the structural resultant changes of source rocks under the influence of the electromagnetic field in the microwave and radio-frequency ranges. The samples from the Bazhenov Formation (West Siberia, Russia) and the Domanic Formation (Ural, Russia) have been tested. It is shown that samples from these formations demonstrate very different heating rates at the same electromagnetic field parameters and the their heating rate depends on the type of the electromagnetic field (radio-frequency or microwave) applied. The temperature of the Bazhenov Formation samples reaches 300 °C within one hundred seconds of the microwave treatment but it slowly rises to 200 °C after twelve minutes of the radio-frequency influence. The samples of the carbonate Domanic Formation heat up more slowly in the microwave field (within two hundred seconds) and to lower temperatures in the radio-frequency (150  $^{\circ}$ C) than the Bazhenov Formation samples. The study of the structure of the samples before and after experiments on the electromagnetic treatment shows fracture formation during the heating process. Numerical simulations of heating dynamics of source rock samples have been based on a simple mathematical model of the electromagnetic influence and main features of heating for different types of source rock have been revealed. The opportunities for application of electromagnetic heating for oil source rock recovery are discussed.

**Keywords:** oil source rocks; dielectric properties; relative permittivity; loss tangent; radio-frequency and microwave electromagnetic fields; mathematical modeling

# 1. Introduction

The relevance of this research is proven by the growing interest in the oil recovery from organic-rich oil source rocks. Two major oil-prone formations located within The Russian Federation are the of Bazhenov and Domanic Formations. Both formations are characterized by very low values of porosity, permeability and complex structure of void space [1–3].

The Bazhenov Formation is one of the richest source rocks in the world which occupies the biggest part of the West Siberian sedimentary basin. The total area of the lateral extension of the formation is more than one million square kilometers (Figure 1). The age of the Bazhenov formation rocks is Upper Jurassic—Lower Cretaceous, consisting of organic-rich shales which are represented with a mixture of carbonate, clay, and siliceous minerals. Thickness varies in the range of 15–80 m with an average of 25 m [4]. According to classification for shales which was proposed by Lazar et al. [5] the Bazhenov formation rocks are presented by various types of organic-rich, siliceous, carbonaceous mudstones with kerogen predominantly of the type II. Total organic carbon is in the range of 1 to 19 wt% [6,7].



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Figure 1. The geographical location of the Bazhenov and the Domanic formations.

The Domanic Formation is located within Volga-Ural and Timan-Pechora sedimentary basins on the European part of the Russian Federation (Figure 1). In terms of the composition, Domanic shales are represented predominantly by organic-rich limestones such as wackestone and packstone, the role of the siliceous rocks is minor. The formation is aged as Upper Devonian (Fransian) and characterized with variable thickness 10–45 m, total organic carbon is in the range of 1–30 wt%, kerogen type II or mixed type II-III [8–10].

Thermal methods of enhanced oil recovery are widely discussed as a promising technology for oil production for this type of unconventional reservoirs. In-situ heating of oil shales up to temperatures in the range of 200–400 °C and keeping them at these temperatures for a certain period of time lead to the generation of mobile hydrocarbons from kerogen due to the pyrolysis process [11].

The use of electromagnetic energy is considered as one of the possible technologies for in-situ heating rocks. Different methods of electromagnetic heating have been previously considered in the number of publications. A comprehensive review of different electromagnetic heating methods (including ohmic heating, radio-frequency/microwave heating, and inductive heating) for enhanced heavy oil and bitumen recovery is provided in [12]. An overview of microwave applications in oil sands bitumen or shale oil production in petroleum upgrading can be found in [13].

The technology considered in [11] implies heating by electrodes placed in parallel wells located at a certain distance. The electrodes are connected by high-voltage cables to a ground-based high-voltage generator of the radio-frequency range. The space between electrodes is heated by the energy of the electromagnetic field absorbed by the rock. The use of a grid of wells is considered a possible way to increase the effectiveness of reservoir stimulation. The application of microwave generator in the well at the depth of shale reservoir has been considered a promising technology in [14]. Solutions are based on electromagnetic power transition using waveguide has been discussed in [15]. To heat rocks to the temperature of kerogen thermal decomposition using these approaches, it is necessary to achieve effective scattering of sufficient power by choosing the optimal values of frequency and the intensity of the influencing field taking into account specific reservoir rock properties.

Investigation of the dielectric properties of source rocks carried out in [16–18] showed that the values of the relative permittivity of the source rock samples are an order of magnitude higher than one for terrigenous rocks. Moreover, the frequency dependences of the loss tangent of the source rock samples have pronounced maxima in the range from 50 to 125 MHz at temperatures of 75 °C and higher. When the temperature increases up to 130 °C, the values of the relative permittivity and the loss tangent for the source rock samples

increase, and at 150 °C they noticeably decrease. The values of the relative permittivity and the loss tangent along the bedding are 1.5–4 times higher than across it. This result can be useful in choosing the direction of the electromagnetic irradiation to influence oil source fields [16,17]. All these results are a good prerequisite for studies of heating source rocks in electromagnetic fields and the possibility of its use in the development of oil source field.

Published results demonstrate intense heating of source rocks in electromagnetic field of a microwave and radio-frequency ranges. In particular, when exposed to microwave field with a frequency of 2.45 GHz, the intensity of heating of shale rock can reach  $500 \degree C/min$  [19–21].

In addition, the effect of the electromagnetic field on the oil source rock in many cases leads to the development of stresses, fracturing, softening, and destruction of the rocks [22,23]. Thermal stresses arise as a result of the inhomogeneous thermal expansion of the rock during the heating process due to the difference in electromagnetic, thermal, and mechanical properties of minerals of rocks (quartz, feldspar, pyrite, clay and carbonates, and other).

The objective of the work is the experimental study of electromagnetic heating of source rocks and structural changes in them on the example of samples representing the Bazhenov and the Domanic Formation. The experimental results are supplemented with the results of numerical modeling to evaluate temperature gradients arising in the bulk of the source rock samples and to determine the limits of temperature growth for Bazhenov and Domanic Formations samples when the time of electromagnetic impact is increased. An important part of the work is the numerical modeling based on a one-temperature mathematical model directed to evaluate the temperature gradients in the volume of the source rock samples.

#### 2. Methods and Materials

#### 2.1. Experimental Set-Ups

Two experimental set-ups for electromagnetic influence on source rock samples were created. The first set-up is for microwave influence based on a magnetron with operating frequency 2.4 GHz with an adjustable output power of up to 1 kW (Figure 2a) and the second one is for radio-frequency treatment that includes a generator with an operating frequency of 13.56 MHz with an adjustable output power of up to 2.5 kW (Figure 2b). During the experiment, both microwave and radio-frequency generators were operated at the same output power of 800 W. To provide thermal insulation and to avoid evaporation of light hydrocarbon fractions sample is placed into a fluoroplastic container. The sample surface temperature is measured by a contactless temperature recorder.



**Figure 2.** Schemes of experimental setups for electromagnetic influence on source rock samples in (**a**) microwave field and (**b**) radio-frequency field.

## 2.2. Scanning Electron Microscopy

Scanning electron microscopy (SEM) was applied for high-resolution imaging with further rock structure characterization [24]. With the Thermo Fisher Scientific (Waltham, MA, USA) Quattro S electron microscope source, rock samples 3–5 mm in size after the experiment carefully prepared from the main samples were analyzed. The SEM tool allows working with an electron beam current range from 1 pA to 200 nA with an accelerating voltage range from 200 V to 30 kV. The maximum available spatial resolution is 1 nm. SEM was performed in secondary electron (SE) and backscattered electrons (BSE) modes with  $\times$ 500–200 K magnification, acceleration voltage 10–15 kV, working distance 9–11 mm, and an image size 1536  $\times$  1094 px.

## 2.3. Rock-Eval Pyrolysis

Investigation of source rock pyrolytic parameters such as quality and quantity of organic matter was performed using HAWK Resource Workstation (Wildcat Technologies, San Diego, CA, USA) according to the Basic/Bulk-Rock method [25,26]. For the analysis, approximately 100 mg of powder from each sample were prepared. The powders were analyzed before the experiments and main pyrolytic parameters were obtained such as total organic carbon (TOC) content, S1, S2, S3.

## 2.4. X-ray Diffraction Analysis

Mineral composition of the samples was investigated using X-ray Diffraction powder analysis technique using Huber G670 with transmission geometry (linear PSD detector, Co tube (Ka1 = 1.78892 Å, 1200 W) and automatic monochromatic system). Approximately 50 mg of powder from each sample were prepared for the analysis. The powders were analyzed before the experiment and the mineral composition was obtained for each sample.

## 2.5. Optical Microscopy

The surface structure of the samples before and after exposure to an electromagnetic field was investigated using an Olympus IX71 optical microscope. Based on the research results, an assessment of the formation and evolution of cracks on the surface of the samples was carried out.

#### 2.6. Mathematical Model

In accordance with the physical model, a sample of oil source rock of cylindrical shape with height h and diameter d is considered. The scheme of the computational domain is shown in Figure 3.



Figure 3. Scheme of the computational domain.

Saturated rock is considered a continuous medium with averaged values of physical properties. It is assumed that the temperature of the phases is equalized instantly.

A one-temperature mathematical model describing the temperature distribution in the oil source rock sample under the electromagnetic field impact consists of the heat conduction equation for a saturated porous medium [27]:

$$C\frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + Q. \tag{1}$$

Here *C* and  $\lambda$  are the volumetric heat capacity and the thermal conductivity of oil source rock, correspondingly.

When electromagnetic field is applied, the internal distributed heat sources arise within the sample due to electromagnetic energy dissipation. Mathematically the thermal effect of the electromagnetic field is described by the density of distributed heat sources *Q* on the right-hand side of Equation (1) which are arisen in the saturated rock as a result of electromagnetic energy dissipation [28]:

$$Q = \frac{\omega \varepsilon_0 \varepsilon \, tg\delta}{2} E_0^2,\tag{2}$$

where  $E_0$  is the electric field strength,  $\varepsilon_0$  is the electrical constant,  $\omega = 2\pi v$  and v are the circular frequency and the frequency of the electromagnetic field, and  $\varepsilon$  and  $tg\delta$  are the relative permittivity and the dielectric loss tangent of saturated rock determined by dielectric measurements [16,17,29].

The Equation (1) is supplemented with the initial and boundary conditions that are in accordance with experiment conditions. At the initial moment of time, the temperature of the rock sample is equal to the room temperature [27]:

$$T|_{t=0} = T_0.$$
 (3)

Boundary condition of heat exchange with the environment determined by the heat transfer coefficient  $\alpha$  is setup at all the sample surfaces [27]:

$$-\lambda \frac{\partial T}{\partial n}\Big|_{surface} = \alpha (T - T_0). \tag{4}$$

## 2.7. Samples

Ten cylindrical samples of source rocks with a diameter of 30 mm and the same height were used in the experiments: five samples from the Bazhenov Formation B1–B5 (Table 1) and five samples from the Domanic Formation D1–D5 (Table 2).

**Table 1.** The photos of the Bazhenov Formation samples and type of the electromagnetic treatment exposed in the experiments.



<sup>1</sup> MW, microwave treatment; <sup>2</sup> RF, radio-frequency treatment.



Table 2. The photos of the Domanic Formation samples and type of electromagnetic treatment exposed in the experiments.

Each of the samples was exposed to one type of electromagnetic treatment (microwave or radio-frequency) as indicated in Tables 1 and 2. To compare the results of microwave and radio-frequency influence to the same source rock, the samples B5 and D5 were divided equally and the resulting parts of the samples were exposed to both types of electromagnetic treatment.

## 3. Results

#### 3.1. Experimental Results

The influence of electromagnetic treatment on the oil source rocks samples were studied using the experimental setups schematically shown in Figure 2.

Before the experiments, pyrolysis analysis and mineral composition investigation of the samples was performed. The results of the pyrolysis analysis are shown in Table 3. The Bazhenov samples are characterized with the TOC range of 3.91–18.48 wt%. The highest value is obtained for sample B1, whereas the lowest one is for sample B3. The Domanik sample D1 is characterized with the highest total organic carbon (TOC) at 4.5%; the samples D2 and D4 have smaller TOC (1.72 wt% and 2.38 wt%, respectively).

Sample	S1, mg HC/g Rock	S2, mg HC/g Rock	TOC, wt%
B1	5.06	84.2	18.48
B2	8.39	71.88	11.01
B3	8.22	21.45	3.91
B4	3.50	10.83	5.45
D1	0.73	12.62	4.5
D2	0.35	2.43	1.72
D4	0.79	8.62	2.38

Table 3. Pyrolysis results of the Domanik and Bazhenov samples.

X-ray Diffraction powder analysis results are given in Table 4. The analysis showed that Bazhenov Formation samples are predominantly represented by quartz and clayrich rocks with variant fractions of quartz and clay components, only the sample B4 is represented with limestone. Domanic Formation samples are quite similar in terms of mineral composition and are defined as limestone.

During electromagnetic treatment, both thermal effect (temperature increase) and structural effect (fractures appearance) on the samples were observed.

Consider first the results of the thermal effect of electromagnetic field on the samples. To quantify the thermal effect of the electromagnetic field let us introduce the average heating rate of the sample  $\dot{q}$  that is defined as the ratio of the temperature change achieved to the duration of the electromagnetic treatment.

Sample	Quartz, wt%	Clay Minerals, wt%	Calcite, wt%	Dolomite, wt%	Pyrite, wt%
B1	52	38	7	0	3
B2	47	49	0	0	4
B3	85	13	0	0	2
B4	12	6	81	0	1
D2	1	0	98	1	0
D3	10	0	87	3	0
D4	3	0	92	5	0

Table 4. X-ray Diffraction analysis results of the Domanik and Bazhenov samples.

In Figure 4 heating dynamics of the source rock samples of Bazhenov Formation B1–B4 and the Domanik Formation D1–D4 under the influence of electromagnetic field is shown.



**Figure 4.** Heating dynamics of source rock samples B1–B4 and D1–D4 under the influence of (**a**) microwave electromagnetic field; (**b**) radio-frequency electromagnetic field.

Microwave treatment causes very rapid heating of all samples (Figure 4a): the temperature of the samples rises up to approximately 300 °C during a short period of time of less than 2 min. Further heating of the samples (above 300 °C) was impossible due to the design features of the experimental setup due to the threat of the heat-insulating cell melting. It can be seen that the Bazhenov Formation sample B2 heats up the fastest ( $\dot{q}_{B2} = 6.1$  °C/s), samples B1 and D2 show approximately the same heating dynamics ( $\dot{q}_{B1} = 2.9$  °C/s,  $\dot{q}_{D2} = 3.6$  °C/s), and the Domanik sample D1 heated up the longest ( $\dot{q}_{D1} = 1.2$  °C/s).

Heating of the samples under the radiofrequency field impact occurs much more slowly and less intense than under the microwave influence (Figure 4b): minutes of radiofrequency treatment, the temperature of only one sample B3 has reached 200 °C. The average heating rate of the samples B3, B4, and D4 are  $\dot{q}_{B3} = 0.25$  °C/s,  $\dot{q}_{B4} = 0.21$  °C/s and  $\dot{q}_{D4} = 0.18$  °C/s, that is they are very close to each other. It should be noted that the sample of Domanik Formation D3 has not actually heated up ( $\dot{q}_{D3} = 0.015$  °C/s). A possible explanation for such unusual behavior is that the sample D3 was recovered from a nonproductive part of a reservoir and it does not contain kerogen at all or contains its insignificant amount.

Figure 5 compares the heating dynamics of the Bazhenov Formation sample B5 and the Domanik Formation sample D5 under the influence of both microwave and radio-frequency electromagnetic fields. In these experiments the same 800 W output power was adjusted for microwave and radio-frequency treatment.



**Figure 5.** Heating dynamics in both microwave and radio-frequency fields of (**a**) the Bazhenov Formation sample B5 and (**b**) the Domanik Formation sample D5.

(a)

As it is shown on Figure 5a the temperature of The Bazhenov Formation sample B5 rapidly rises from the room temperature up to 239 °C in the radio-frequency field  $(\dot{q}_{B5}^{RF} = 1.2 \text{ °C/s})$  and up to 301 °C in the microwave field  $(\dot{q}_{B5}^{MW} = 1.5 \text{ °C/s})$  after three minutes of the electromagnetic influence. The Domanic Formation sample D5 demonstrates a significantly lower intensity of heating (Figure 5b). After nine minutes of the radio-frequency field treatment ( $\dot{q}_{D5}^{RF} = 0.09 \text{ °C/s}$ ) it was ultimately heated up to 70 °C and up to 94 °C after eight minutes of the microwave treatment ( $\dot{q}_{D5}^{MW} = 0.15 \text{ °C/s}$ ).

(b)

Thus, it can be concluded that electromagnetic influence (no matter microwave or radio-frequency range) provides faster and more intensive heating of the Bazhenov Formation samples than the Domanic Formation samples. This is likely due to the fact that the composition of the Bazhenov Formation includes clays and silica minerals where one can observe additional absorption of the electromagnetic field energy.

The second important aspect of the interaction between the electromagnetic field and the oil source rock is the structural changes occurring in the samples. Fracture networks were found to appear under the electromagnetic field impact in the source rock samples. The formation of fractures of various scales was observed in experiments with all the samples under both the microwave and radio-frequency fields impact (except sample D3, which did not interact with the electromagnetic field at all as it was stated above). Thermoelastic stresses caused fracture formation in the rock due to the rapid local heating of polar hydrocarbon components that the sample contains.

Before the experiment on the electromagnetic treatment, the surface of the samples was analyzed by optical microscopy. After the experiment, the surface of the samples was examined again. In this case, one could observe macrocracks using an optical microscope and microcracks using a scanning electron microscope.

Figure 6 represents the photos of the microstructure of samples B3 and D4 before the electromagnetic treatment and after the radio-frequency field exposure. The long vertical fracture which formed as a result of the radio-frequency field influence is clearly visible on the surface of the Bazhenov Formation sample B3. On the contrary to sample B3, small cracks have just started to appear on the surface of the Domanic Formation sample D4. The difference can be explained by the fact that sample B3 was heated up to the temperature of 201 °C while sample D4 reached the maximum temperature of 152 °C.





**Figure 6.** Photos of the microstructure of samples B3 and D4 (**a**) before the treatment and (**b**) after the radio-frequency treatment ( $48 \times$  magnification).

Samples B1 and D2 were heated up to approximately the same temperatures (286 °C and 293 °C, respectively) under the microwave field impact. Therefore, larger cracks formed on the surface of both samples after the microwave influence (Figure 7).





Figure 8 shows the photos of the microstructure of the Bazhenov sample B5 before the electromagnetic influence and structural changes occurred in the sample after the microwave and radio-frequency treatments.

After 15 s of the radio-frequency treatment of sample B5, a dielectric breakdown of the sample occurred and the sample split in two (Figure 8c).



**Figure 8.** Photos of the microstructure of the Bazhenov Formation sample B5 (**a**) before the treatment; (**b**) after the microwave treatment; and (**c**) after the radio-frequency treatment ( $48 \times$  magnification).

The fractures on the sample were recorded as early as 10 s after the onset of microwave exposure when the sample temperature exceeded 50 °C. Intensive growth of fractures was observed within 40 s. During this time, the sample was heated up to 140 °C. Further microwave treatment did not change the structure of the sample surface. The formation of new fractures apparently occurred in the volume of the sample. The final configuration of fractures is shown in Figure 8b.

Scanning electron microscope images of the surface of several samples after electromagnetic treatment are shown on Figure 9. A number of intense microfractures oriented along the lamination were found in sample B1. It is obvious since the sample has a thin layered microstructure formed by clay minerals as well as thin organic matter lenses which are 1–10  $\mu$ m thick and 5–50  $\mu$ m long. The other samples have a massive structure and do not have such inhomogeneity except for sample D3. The thin layering in sample D3 is caused by elongated calcite detritus 10–50  $\mu$ m in thickness and often more than 100  $\mu$ m in length. However, there were not cracks in the sample.



**Figure 9.** Scanning electron microscope images of samples (**a**) B1, D1 and (**b**) B3, D3 after the electromagnetic treatment.

## 3.2. Numerical Results

Numerical modeling of the microwave and radio-frequency influence on oil source rocks which was based on the mathematical model Equations (1)–(4) and written in cylindrical coordinate frame was carried out. The finite volume method was implemented for the numerical solution of partial differential Equation (1).

The following values of the parameters were taken for the calculations: d = 0.03 m, h = 0.03 m,  $\lambda = 1.71$  W/(m · K),  $C = 2.74 \cdot 10^6$  J/(m<sup>3</sup> · K) [30].

The crucial point for an adequate numerical simulation of the electromagnetic exposure process is the correct assignment of the density of the distributed heat sources  $q_{EM}$ given by the Formula (2). According to this formula, the value of the distributed heat sources density depends on the distribution of the electric field strength in the medium and on the dielectric properties of the medium. Since the wavelength of electromagnetic radiation is larger than the characteristic dimensions of the samples considered, the dependence of the distributed heat sources density on the electric field strength can be neglected. Therefore, in numerical simulation the distributed heat sources density was taken as a constant value which was uniformly distributed over the volume of the sample. The particular value of the distributed heat sources density was determined in the process of the mathematical model validation with the results of the experimental studies of the microwave and radio-frequency influence on the source rock samples [19].

Whereas the temperature of the sample surface was measured in the experiments, the numerical simulation allows one to obtain the temperature at all points of the sample. The typical temperature distribution in the volume of the oil source rock samples under the microwave and radio-frequency impact are shown for two Bazhenov Formation samples B2 and B3 in Figure 10. This figure shows that the temperature is approximately 20 °C higher at the sample center than on its surface. The surface temperature decreases due to the intensification of heat exchange with the environment when the sample temperature increases.



**Figure 10.** Temperature distribution in (**a**) sample B2 after 45 s of the microwave treatment; (**b**) sample B3 after 10 min of the radio-frequency treatment.

Due to the presence of heat transfer from the side, upper and lower surfaces of the sample, the temperature is distributed unevenly along the radius and the height. In this case, high values of the temperature gradient appear and stimulate the emergence of powerful thermoelastic stresses in the sample. It leads to formation of cracks under certain conditions. If the inhomogeneity of the absorption of the field energy in the medium is observed, the temperature gradient may turn out to be much higher.

Figure 10 shows that there is a gradual increase in the temperature throughout the sample. The qualitative picture of the temperature distribution is identical to the case of the microwave exposure. Temperature differentiation is also observed in the middle and vertical sections. The temperature in the center of the sample is higher than that at the surface. As in the case of the microwave exposure, the temperature difference between the center and the upper part reaches 3 °C; between the center and the lateral surface it rises up to 20 °C and increases with time. Such inhomogeneity of the absorption of the field energy and the arising temperature gradients in a real medium may turn out to be much higher. In this case, the characteristic time of the radio-frequency heating of the samples to a temperature identical to the microwave action increases considerably. This is due to the

change in the absorption capacity of the substance saturating the samples with a change in the frequency of the applied field [29]. However, it should be noted that the coverage factor of the radio-frequency exposure is significantly higher than that of the microwave exposure. If it is necessary to heat only the bottomhole zone, it is advisable to use the microwave range but for heating the zone far from the bottom one should resort to the radio-frequency range.

Figures 11 and 12 show the temperature distribution in the middle cross section of the Bazhenov Formation samples B2 and B3 at three consecutive times.



**Figure 11.** Temperature distribution in the middle section of the sample B2 under microwave exposure at different points in time: (a) 43 s; (b) 44 s; (c) 45 s.



**Figure 12.** Temperature distribution in the average cross section of sample B3 under radio-frequency exposure at different times: (**a**) 9 min; (**b**) 10 min; (**c**) 11 min.

One can see that under the microwave field impact the heating rate of the sample is very intensive. In 45 s of the electromagnetic exposure the sample heats up to over 300 °C (Figure 11c).

To compare the results of physical and mathematical modeling, the volume-averaged the temperature was averaged over the sample volume  $V_s$  by the expression:

$$\langle T \rangle = \frac{1}{V_s} \int_{V_s} T(r, \varphi, z) dV.$$
(5)

Comparison of the experimental data and the numerical modeling results for heating dynamics of source rock samples under the microwave and radio-frequency electromagnetic fields impacts is shown on Figure 13. The good agreement between the experimental and computational data was obtained. One can observe the numerical curves coincide with the experimental points taking into account the measurement accuracy.



**Figure 13.** Comparison of the experimental data and the numerical modeling results for heating dynamics of source rock samples under the influence of (**a**) the microwave electromagnetic field and (**b**) the radio-frequency electromagnetic field.

The analysis of the curves that is shown in Figure 13a allows one to conclude that an increase in the time of the microwave treatment will lead to a further increase in the temperature of all the samples and will allow to reach the temperatures of 400–500 °C required for the pyrolysis of kerogen. The same conclusion cannot be drawn for the case of the radio-frequency treatment since it is clearly seen in Figure 13b that the heating rate decreases and an increase in treatment time will most likely not lead to a significant increase of the sample temperature.

However, it should be noted that there is some difference in the qualitative behavior of temperature under the microwave impact in physical and numerical experiments (Figure 13a). After the temperature reached a certain value, the heating rate of the samples was decreased. The same was observed with the intensity of the temperature rise. But the numerical results demonstrate a linear increase in temperature with constant heating rate. Possible explanation for this discrepancy is a change in the dielectric parameters of the source rock that occurs with an increase in the temperature of the samples, which was not taken into account in the mathematical model.

Table 5 compares the average heating rate of the samples obtained in the experiments  $\dot{q}_{exp}$  and those ones which were calculated in numerical modeling  $\dot{q}_{num}$ . Numerical simulation gives a slightly overestimated value of the heating rate in comparison with the experimental data for the reason that was described above.

	Microwave Influence			ce	Radio-Frequency Influence			
Sample	<b>B</b> 1	B2	D1	D2	B3	<b>B4</b>	D3	D4
$\dot{q}_{exp}, ^{\circ}C/s$ $\dot{q}_{num}, ^{\circ}C/s$	2.90 3.00	6.10 6.72	1.20 1.25	3.60 3.70	0.25 0.26	0.21	0.015 0.015	0.18 0.18
$Q, W/cm^3$	8.99	19.48	4.21	10.96	1.22	1.04	0.07	0.87

**Table 5.** The average heating rate of the samples  $\dot{q}$  and the density of distributed heat sources in the samples Q arising under the electromagnetic impact.

Table 5 also represents the value of the density of distributed heat sources arising under electromagnetic exposure which was used for the numerical modeling. Obviously, such a different value of the density of heat sources is due to the difference in the chemical composition of the samples. It can be concluded that the dielectric properties of the Domanic Formation samples are observed in such a way that the dissipation of the electromagnetic energy is small at the given frequency of the radio-frequency field.

# 4. Discussion

It was discovered that the average heating rate of the Bazhenov Formation samples can be an order of magnitude higher than the one of the Domanik Formation samples both in the microwave and radio-frequency fields. For instance, one of the Bazhenov Formation samples had the average heating rate in the microwave field of  $1.5 \,^{\circ}\text{C/s}$ , and in the radiofrequency field it was slightly less (1.2  $^{\circ}$ C/s, at the same output power of the magnetron and radio-frequency generator). At the same time, the corresponding values of the average heating rate for the Domanic Formation sample were 0.15 °C/s (microwave) and 0.09 °C/s (radio-frequency). This effect may be caused by several factors. The first one is the mineral composition. According to the XRD data Bazhenov Formation samples contain clay minerals (up to 49 wt%) where one can observe additional absorption of the electromagnetic field energy. The second factor is the organic matter composition. Bazhenov Formation samples are considerably enriched with light hydrocarbons (S1 parameter varies in the range of 3.50–8.39 mg HC/g rock) whereas Domanik Formation samples do not share the same properties. The third factor has to do with differences of water amount in the rocks. According to Kazak et al. [31,32], Bazhenov Formation rocks contain an order of magnitude which contain more water than Domanik Formation rocks (1-8 wt% and 0.1–0.5 wt%, respectively).

The comparison of heating rates in the separate microwave and radio-frequency field experiments with the mineral composition shows no obvious trends. This may be explained by similar properties of the minerals with regard to the electromagnetic field impact in the particular experiment conditions. However, one should note that the combination of S1 and S2 pyrolysis parameters does make difference. The samples with lower S1 tend to have a lower heating rate (sample D2) whereas the samples with higher S1 have a significantly higher heating rate (samples B1–B4). This observation means that light hydrocarbons may directly influence the heating of the rocks under the electromagnetic impact.

The developed mathematical and computer models of the electromagnetic heating process make it possible to predict the dynamics of sample heating. To obtain adequate results of the numerical modeling, it is important to correctly specify the function of the density of the distributed heat sources. One should take into account the temperature dependences of the dielectric properties of the source rock and the inhomogeneity of the electric field distribution in the sample.

The results of the numerical modeling have confirmed that the sample temperature can be increased up to 400–500 °C if one increases the time of the microwave exposure which is required for the pyrolysis of kerogen. A completely different dynamics of temperature was observed under the radio-frequency impact; the samples were heated slowly and it was not possible to reach the temperature of kerogen pyrolysis since the heat exchange with the environment turned out to play a significant role.

The results of the mathematical modeling have shown that the density of the distributed heat sources under the microwave exposure is an order of magnitude higher than under the radio-frequency exposure. This means that the microwave exposure gives a more intense but local effect which leads to cracking of the samples. The radio-frequency exposure does not lead to the same effect. However, it can lead to an increase in the radio-frequency exposure coverage factor as compared to the microwave exposure. It was also found that in the process of the radio-frequency and microwave exposure in the rock samples, in addition to reaching high temperatures, temperature differentiation is also observed; the temperature difference in the center of the sample and on its surface can reach the point of 20 °C and more. In this case, if the inhomogeneity of the absorption of the field energy in a real medium is observed, the temperature gradient may turn out to be much higher. Such high values of the temperature gradient stimulate the appearance of powerful temperature stresses in the sample which lead to formation of fractures under certain conditions.

## 5. Conclusions

In conclusion, it should be noted that the results of the experimental and numerical studies show the presence of both thermal and force effects of the microwave (2.4 GHz) and radio-frequency (13.56 MHz) electromagnetic field on the oil source Bazhenov and Domanic rock samples. The thermal effect of the microwave treatment on the source rock samples is much more intense than that of the radio-frequency influence. The temperature of the investigated Bazhenov Formation samples reached 300 °C within one hundred seconds under the microwave treatment, but the sample temperature slowly rose up only to 200 °C after twelve minutes of the radio-frequency influence. This is due to the fact that the radio-frequency field mainly affects the oil polar components and there is no mature oil and polar components in the source rock samples.

An important and encouraging result of the electromagnetic exposure is the oil source rock sample cracking. The formation of fractures was observed on all the samples under both the microwave and radio-frequency exposure. Achievement of high temperatures under the microwave exposure in under relatively short period of time (several minutes) leads to the appearance of thermoelastic stresses in the samples. The greater the difference in the heating intensity of individual components and phases is, the more noticeable the stresses are. This phenomenon is confirmed by the formation of cracks which are observed under the microwave exposure on all the samples.

The scientific results which were obtained in this work and the accumulated world experience which was considered in the practical implementation of the microwave and radio-frequency treatment in situ make it possible to believe that these methods of treatment will be successfully implemented for oil source rock field development in the nearest future. For the successful application of the electromagnetic technologies it is necessary to carry out a deeper experimental study of real source rock samples for a particular field and the detailed mathematical modeling of the electromagnetic treatment process.

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