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APPLICATION OF ACTIVE THERMOMETRY TECHNOLOGY IN THE DETERMINATION OF THE BEHIND-THE-CASING FLOW INTO UPPER AQUIFER

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ABSTRACT

Based on the results of numerical mathematical modeling, the application of active thermometry technology to determine of the behind-the-casing flow into upper aquifer is considered. The technology of active thermometry be confined in local induction heating of a section of a metal casing in a well, recording the temperature of the inner wall of the casing at the heating site, as well as above and below it. Mathematical modeling is based on the numerical solution of the Navier-Stokes equations and heat transfer equations, taking into account convection, thermal conductivity and a heat source in the Ansys Fluent software package. Two variants are modeled, in the first variant there is gas in the well in the logged section, in the second – water, which corresponds to a different position of the fluid level in the well relative to the logged section. The criteria are shown to determine the presence of the behind-the-casing flow on a series of surveys of the casing temperature distribution in depth: the asymmetry of the casing temperature distribution curves in depth relative to the middle of the heating section, the movement of the maximum point on the temperature curves in time upward in the direction of the behind-the-casing flow. It is shown that the results of surveys the temperature of the casing wall (in depth, in time) can be used to quantify the flow rate of the behind-the-casing flow.

Keywords: active thermometry; temperature field; induction heating; aquifer; ecological monitoring; behind-the-casing flow.

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1. Introduction

For oil regions with a large number of drilled wells, monitoring the condition of the upper aquifer is an important environmental task. One of the common causes of pollution of aquifers is the behind-the-casing flow. The inflow of water from the reservoir and pumped into the well occurs through the leaky space of the well outside the casing. The problem is aggravated at a late stage of field development, when various chemically active liquids are pumped into wells to increase oil recovery, and hydraulic fracturing is carried out. In the presence of the behind-the-casing flow, these liquids can flow not only into productive formations, but also aquifers. This leads not only to negative environmental consequences, but also to a decrease in the effectiveness of exposure to productive formations due to injection liquid leaks [1, 2]. In this regard, the identification of sources of pollution of aquifers is an important task.

To date, the method of highly sensitive thermometry in combination with acoustic noise logging and pulsed neutron logging has become the most widespread for determining of the behind-the-casing flow [3-5]. The thermometry method is based on the registration of natural thermal disturbances caused by the filtration of liquid in the borehole annulus. Acoustic noise logging allows you to identify the noise that occurs in the fluid flow. Pulsed neutron logging data is sensitive to the presence of certain chemical elements (hydrogen, chlorine) contained in the injected fluid. This makes it possible to control the oil saturation of formations, and an increase in the water saturation of non-target formations (into which liquid is not pumped) is a sign of the behind-the-casing flow [6, 7].

It should be noted that the above methods have certain disadvantages. In particular, with traditional thermometry, a temperature sensor is located inside the casing and registers the temperature of the fluid (gas or liquid) inside the casing. This leads to a decrease in the sensitivity of the thermal detector readings to thermal processes in the casing space [8]. The disadvantages of acoustic noise measurement include the difficulty of isolating a useful signal, a significant influence on the sensor readings of background noise that is not associated with casing flow (in a casing, in a liquid inside a casing). As a result, the ambiguity of the definition of the behind-the-casing flow increases [9]. Thus, it is relevant to develop effective methods and technologies that, in combination with existing ones, will help to increase the reliability of determining of the

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behind-the-casing flow into aquifers. This paper considers the application of active thermometry technology to identify of the behind-the-casing flow into upper aquifers.

2. Technology and equipment of active thermometry

Among modern technologies for diagnosing well conditions, one of the most promising approaches is active thermometry. This method represents an advanced version of traditional thermometry. The key feature of this technology is the controlled formation of temperature anomalies in the area of interest within the well. The practical implementation of the method is based on creating a localized inductive effect on a specific section of the casing string. The thermal energy generated in the casing is transferred to the fluid inside the well and to the external space. If the behind-the-casing flow is present, convective heat transfer intensifies, leading to deformation of the temperature field near the heating zone. Analyzing the spatial distribution of temperature and its dynamics over time allows for the identification of annular flow and the evaluation of its parameters, such as velocity and direction [10].

At the Department of Geophysics of the Ufa University of Science and Technology, a prototype of a downhole instrument for active thermometry has been developed and tested. The device features a modular architecture (fig. 1), providing flexibility in solving various production logging and oil producing problem. For instance, the inductor module can be used separately for heating the near-wellbore zone and the well itself, as well as for melting paraffin and hydrates. The distributed temperature sensor module can be positioned above or below the inductor module, or on both sides simultaneously. The presence of sensors pressed against the casing enhances the temperature module's sensitivity to processes occurring in the external space [11].

The device consists of the following functional modules:

- Positioning and data transmission module (base module);
- Induction heating module;
- Distributed temperature sensor module.

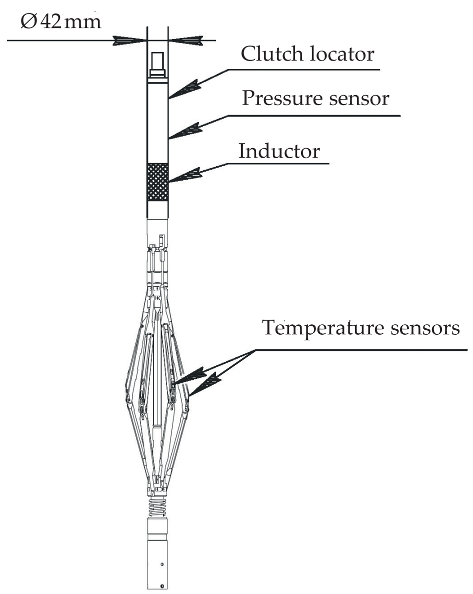


Fig. 1. Active thermometry tool

The positioning and data transmission module ensures the determination of the device's depth within the well, collects information from sensors, and transmits it to the surface processing unit. The induction heating module, designed to create thermal impact on the casing, provides a power output of up to 5 kW, allowing the heating mode to be adapted to various geothermal conditions and well characteristics. The distributed temperature sensor module includes six temperature sensors pressed against the inner surface of the casing using lever mechanisms, as well as one sensor for measuring the temperature of the well fluid. The temperature measurement range of the sensors is 0 to 150 °C, with a resolution of at least 0.003 °C. To minimize external influences, the thermosensitive elements of the sensors are thermally insulated from the fluid flow inside the casing [12].

The application of active thermometry is not limited to detecting behind-the-casing flows. Analyzing the temperature field dynamics also allows for the evaluation of fluid flow rates within the wellbore, as confirmed by research findings presented in [13-15]. The study [13] focuses on the use of active thermometry technology for determining fluid flow rates in horizontal wellbores. The results include numerical modeling of the thermal field and experimental verification of the model's accuracy under different flow conditions. The study demonstrates that the movement speed of thermal markers depends on the fluid flow velocity within the wellbore, making it possible to determine the flow rate by analyzing temperature field dynamics. In studies [14, 15], the successful application of active thermometry for assessing oil and water flow rates in stratified two-phase flow is demonstrated. Beyond production geophysics, electromagnetic (including inductive) heating in the well is also used for heating the near-wellbore zone and the well itself to enhance production, melting paraffin-hydrate deposits, reducing oil viscosity, breaking water-oil emulsions [16-18].

It should also be noted that active thermometry technology, based on induction heating, is characterized by a high degree of controllability and safety. The required heating of the casing string to register temperature anomalies is only a few dozen degrees, eliminating the risk of deformation or structural integrity failure of the well. By varying the power and duration of heating, the thermal impact can be precisely adjusted to match specific conditions. Modern high-sensitivity thermometers can detect temperature changes with an accuracy of hundredths of a degree, minimizing the need for significant heating. Regarding reservoir temperature ranges, active thermometry technology has no strict limitations. Induction heating creates additional contrasting thermal anomalies, which are detected independently of the initial temperature. However, at high reservoir temperatures, the influence of natural convection within the wellbore increases, which may complicate data interpretation and the detection of behind-the-casing flows, especially those directed upward. In such conditions, it is essential to analyze temperature data in detail and account for the effects of convective processes.

3. Research methods

This study aims to analyze how behind-the-casing flow influences the thermal field in a shut-in well when the casing string undergoes induction heating. To achieve this goal, numerical modeling of thermal processes in a well with induction heating was performed using the ANSYS Fluent software package. The model included: inductor, fluid inside the casing (water or gas), casing string, behind-the-casing flow, cement sheath, surrounding rock formations (fig. 2). The flow rate of the behind-the-casing flow (q) and the type of fluid inside the casing (liquid or gas) were varied. The presence of gas in the wellbore is considered because, in low reservoir pressure wells, the dynamic fluid level may drop below the depth of the freshwater aquifer.

Governing equations: The fluid flow is described by the Navier-Stokes equations using the Boussinesq-Oberbeck approximation [19, 20]. Heat transfer in the fluid occurs due to convective heat transfer and thermal conduction [21].

$$\frac{\partial T}{\partial t} + \upsilon\nabla(T) = a\Delta T \quad (2)$$

where υ – velocity, a – thermal diffusivity of the liquid.

The temperature distribution in the inductor, casing string, cement sheath, and surrounding rock formations (regions 1, 3, 5, and 6) is governed by the unsteady heat conduction equation [22]:

$$c\rho\frac{\partial T}{\partial t} = \lambda\Delta T + Q(z) \quad (4)$$

where λ – coefficient of thermal conductivity, c – specific heat capacity, ρ – density, kg/m^3; $Q(z)$ – specific power of the heat generation (the source term takes a non-zero value in the region of 6).

At the initial time, the temperature throughout the entire model is assumed to be constant at 50 °C. The model's lower boundary has a set flow velocity and temperature, while the upper boundary maintains constant pressure. Thermophysical properties (thermal conductivity (λ), specific heat capacity (c), and density (ρ)) are defined by a reference table [23].

The calculations also take into account: the viscosity of a liquid (water) is 1 MPa·s, the viscosity of a gas is 0.018 MPa·s, the coefficient of thermal expansion for a liquid is 0.00053 K^{-1}, for a gas – 0.00367 K^{-1}.

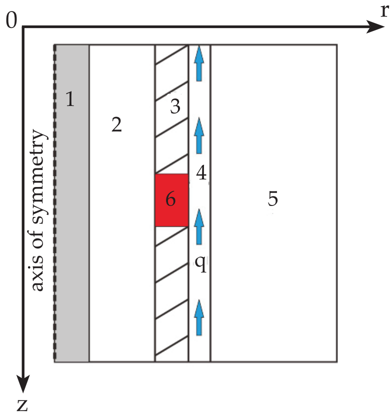
In the numerical simulation of fluid flow, the Navier-Stokes equations were solved using the PISO algorithm, which provides higher accuracy compared to the SIMPLE method when modeling coupled hydrodynamic and heat transfer problems. For the discretization of convective terms, the QUICK scheme was chosen, while gradient calculations were performed using the Green-Gauss Node-Based method. The selection of the PRESTO! scheme for pressure gradient approximation was justified by the need for an adequate representation of swirling flow effects [24].

4. Analysis of simulation results

The numerical simulations consider behind-the-casing flow rates of 1, 2, and 5 m³/day. The induction heating power used in the calculations is 1 kW, with a heating cycle duration of 20 minutes. The 1 kW power level was selected based on the technical specifications of the downhole inductor. Preliminary calculations using an analytical model [19] have shown that the chosen parameters provide sufficient heating of the casing string to enable the detection of temperature anomalies associated with behind-the-casing flow.

The results of calculating the temperature in the casing (temperature changes relative to the initial $\Delta T = T - T_0$) at the flow rate of the behind-the-casing flow q = 2 m^3/day are shown in figure 3. The heating section 2.8–3.2 m is highlighted in color. There is gas in the casing, the liquid level in the well is located below the research interval. For comparison, the results of modeling in the absence of the behind-the-casing flow are also presented. The presence of the behind-the-casing flow leads to a significant change in the shape of the temperature curves. Firstly, the heating value of the casing in the induction heating section is reduced. In the absence of the behind-the-casing flow, the heating of the casing reaches more than 60 °C in 20 minutes of heating, in the presence of the behind-the-casing flow, the heating does not exceed 12 °C. Secondly, in the presence of the behind-the-casing flow, an asymmetry of temperature curves occurs relative to the middle of the heating section, without overflow this asymmetry is not observed. The heat generated in the induction heating zone is primarily transported upward by the fluid flow, resulting in temperature disturbances of 5–10 °C at distances of up to 3 meters above the heater. Below the heating zone, temperature changes are negligible. The temperature field dynamics are also characterized by the shift of the maximum temperature point over time, moving in the same direction as the behind-the-casing flow.

Figure 4 shows the curves of the temperature distribution over depth 5 minutes after the heating stop at different flow rates of the behind-the-casing flow.



1 – downhole device with induction heater,
2 – injected liquid inside the casing, 3 – casing,
4 – channel of the behind-the-casing flow of liquid,
5 – cement ring and rocks, 6 – heating site,
Q – flow rate of liquid in the casing,
q – flow rate of the behind-the-casing flow

Fig. 2. Geometry of the well model with the behind-the-casing flow

Table

Thermophysical properties of the regions

	λ, W/(m·K)	C, J/(kg·K)	ρ, kg/m^3
Inductor housing (area 1)	0,48	920	1500
Water (area 2, 4)	0.65	4200	1000
Gas (area 2)	0.02	1000	1.22
Metal (area 3, 6)	50	500	8000
Cement ring + rock (area 5)	2	1000	2500

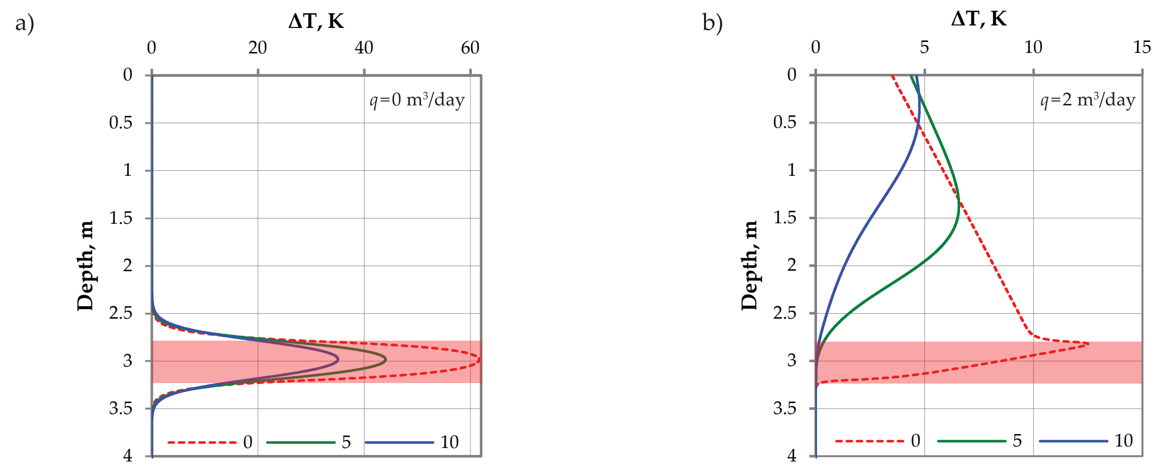


Fig. 3. Casing temperature after the end of induction heating (a) without behind-the-casing flow, b) with behind-the-casing flow), curve cipher – time after heating stop, min

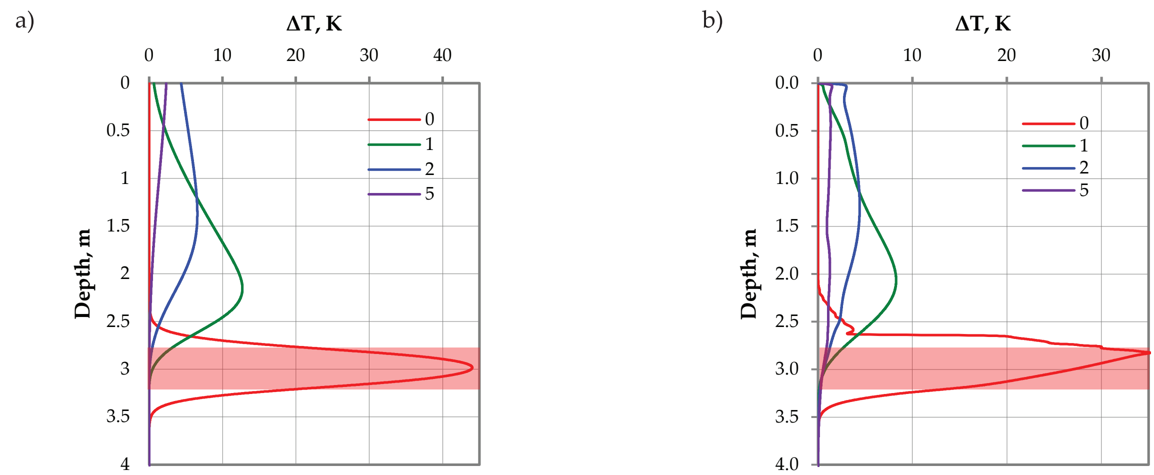


Fig. 4. The temperature of the casing 5 minutes after the end of induction heating (a) in the casing, b) in the gas, inside the casing), the cipher of the curves is the flow rate of the behind-the-casing flow, m³/day

The flow rate of the behind-the-casing flow affects the temperature in the casing and inside it, in the gas. The temperature curves in the casing and inside the casing in the gas have a similar shape, while the temperature in the gas is lower. With an increase the rate of the behind-the-casing flow, on the one hand, the maximum value of temperature disturbances decreases, since the intensity of heat rejection from the casing increases. On the other hand, due to an increase the rate of the behind-the-casing flow, the rate of convective heat transfer increases, as a result, the maximum temperature point moves higher. For example, with the rate of the behind-the-casing flow of 1 m^3/day, the maximum temperature point moves 0.6 m above the heating area, the temperature anomaly in the casing is about 13 °C, with a flow rate of 2 m^3/day, the maximum temperature point is 1.4 m above the heating area, the temperature anomaly in the casing is 6.5 °C. These features enable quantitative analysis and numerical estimation of behind-the-casing flow rate from post-heating casing temperature data.

The presence of the behind-the-casing flow can also be established on the basis of measurements «at the point» of the casing temperature dynamics above the induction heating section (fig. 5).

In the absence of the behind-the-casing flow, there is no temperature anomaly in the casing at distances of 1 and 2 m above the heating site. One of the possible causes of temperature anomalies above the heating site is natural convection in the gas, however, the calculation results showed that its effect is small. Temperature disturbances also propagate upwards due to vertical thermal conductivity (mainly along a metal casing, since its thermal conductivity is maximum relative to cement or rocks), however, calculations have shown that even in 1 hour the effect of thermal conductivity is limited by a distance of about 0.4 m. Thus, the only source of temperature anomalies in figure 5 is convective heat transfer due to the behind-the-casing flow. The analysis of temperature distribution graphs along the casing and the temperature dynamics curves recorded at points 1 and 2 meters above the heating zone revealed a consistent pattern: an increase in the behind-the-casing flow rate is accompanied by a decrease in the maximum temperature of the casing string and a simultaneous acceleration of temperature disturbance propagation to the measurement points. For example, at a distance of 1 m above the heating site, with a rate of the behind-the-casing flow of 1 m^3/day, the maximum temperature anomaly in the casing reaches 11 °C, with a rate of the behind-the-casing flow

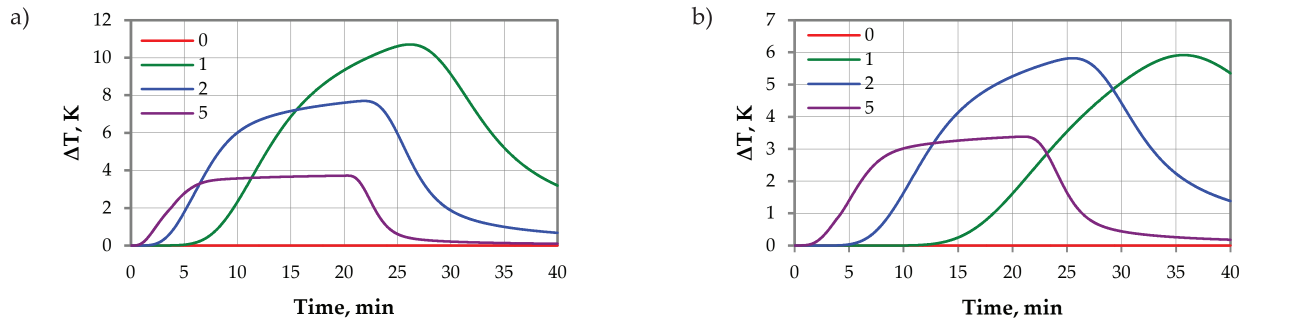


Fig. 5. Dynamics of changes in the temperature of the casing by 1 m (a) and 2 m (b) above the heating site, the cipher of the curves is the rate of the behind-the-casing flow, m³/day

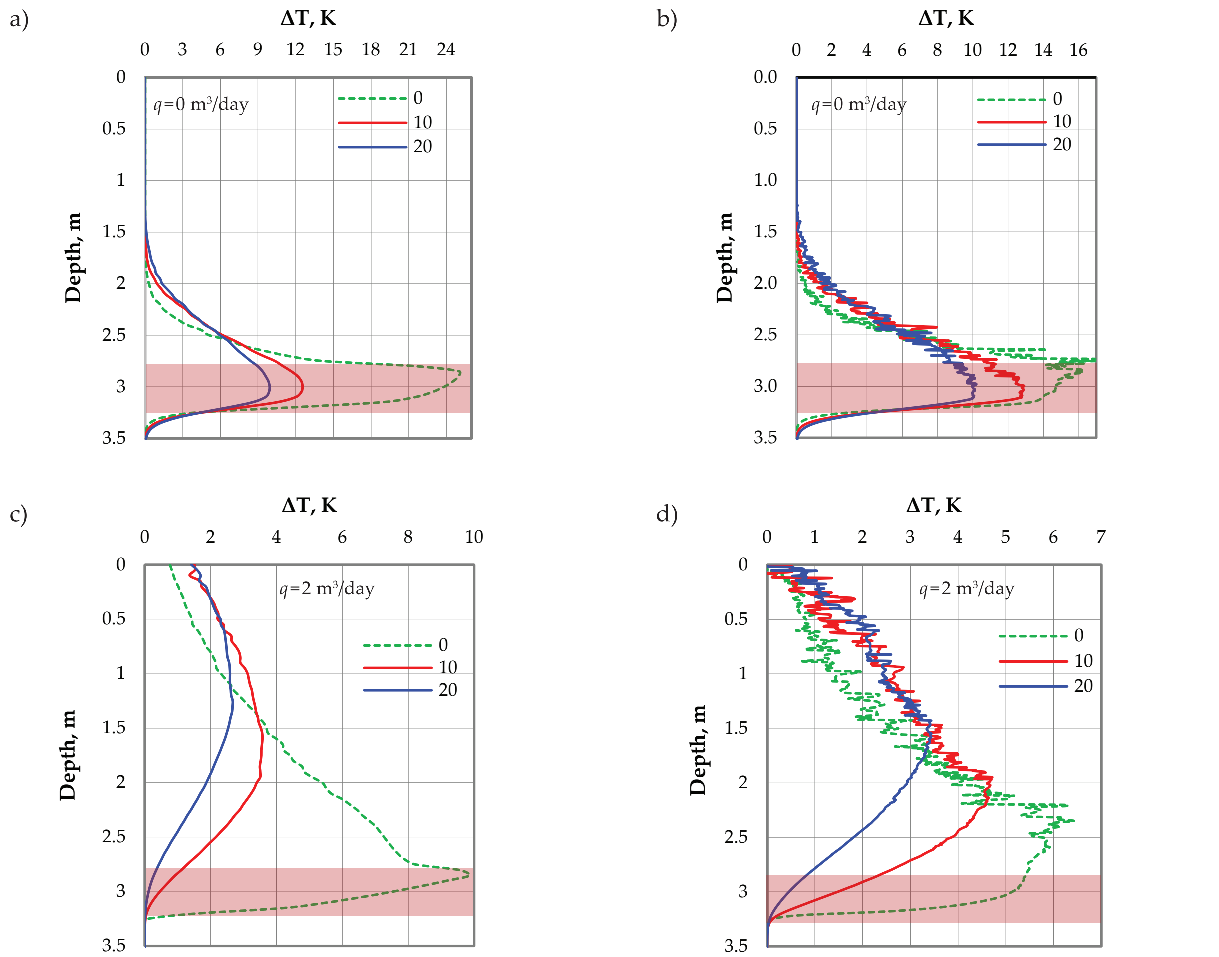


Fig. 6. Temperature in the casing (a, c) and in the liquid (b, d) after the end of induction heating (a, b – without the behind-the-casing flow, c, d – the behind-the-casing flow with a rate of 2 m³/day), curve cipher – time after heating stop, min

of 5 m³/day, the maximum temperature anomaly is about 4 °C. Measurements of temperature dynamics «at a point» above the heating site can also be used to quantify the flow rate of the behind-the-casing flow.

Similar calculations were performed for the case when there is liquid in the casing. This case is realized when the liquid level in the well is located above the research interval. The results of calculating the temperature distribution in the casing and in the liquid in the absence and presence of the behind-the-casing flow are shown in figure 6.

The composition of the fluid in the borehole has a significant effect on the thermal field, if we compare the calculation results for different fluids (gas, liquid), the following main differences can be noted [25]:

1) The heating of the casing and the fluid itself is lower when there is water in the casing. For example, in the absence of the behind-the-casing flow for a well with gas, the heating of the casing in the heating area reaches more than 60 °C, for a well with water, the heating of the casing does not exceed 25 °C. This is due to the significantly lower thermal conductivity and heat capacity of the gas compared to water. In the presence of the behind-the-casing flow, the difference in temperature readings for different fluids decreases to a value of 2–4 °C, since the contribution of heat exchange of a casing

with the behind-the-casing flow to the temperature field increases.

2) When water is present inside the casing string, an asymmetry in the temperature distribution curves along the casing depth occurs even in the absence of behind-the-casing flow. Temperature disturbances propagate upward up to 1.5 meters above the heating zone. This phenomenon is caused by the development of natural thermal convection in the fluid, leading to temperature anomalies in the casing that are not related to behind-the-casing flow.

3) As a result of natural thermal convection developing within the fluid volume, short-term temperature fluctuations are recorded, characterized by high frequency and an amplitude range of 0.5–1 °C. These observed temperature oscillations are associated with local mixing processes and heat exchange within the fluid. However, temperature measurements on the casing surface do not reveal similar fluctuations. This is due to both the smoothing effect of the metal's thermal conductivity and its thermal inertia, which prevents rapid temperature changes.

Conclusions

1. Based on the results of numerical modeling in the Ansys Fluent engineering package, the application of active thermometry technology for determining of the behind-the-casing flow of liquid into upper aquifer is considered. 2 variants are modeled when there is gas (case I) and water (case II) in the well in the research interval.
2. In the case of a gas-filled well (case I), induction heating leads to a significant increase in the casing temperature within the heating zone, reaching over 60 °C in the absence of behind-the-casing flow. However, when behind-the-casing flow is present, intensive heat dissipation occurs, reducing the casing temperature by more than five times. The degree of casing cooling increases with the flow rate of the behind-the-casing flow. It has been shown that the presence of behind-the-casing flow causes significant asymmetry in the temperature field distribution along the casing. The amplitude of temperature disturbances reaches 5–10 °C within 3 meters above the heating zone. The formation of high-temperature zones 1–2 meters above the heating area serves as a clear indicator of behind-the-casing flow presence. The obtained results substantiate the feasibility of quantitatively assessing the fluid flow rate in the annular space by analyzing a series of temperature profile measurements along the casing wall after heating has stopped, as well as by monitoring temperature changes over time at a fixed point above the heating zone.
3. For liquid-filled wells (case II), simulation results revealed a significant influence of natural thermal convection on the temperature field. Notably, asymmetry in the temperature profile within both the casing and the fluid is observed even in the absence of behind-the-casing flow, and temperature disturbances propagate over considerable distances (up to 1.5 meters) above the heating zone. This introduces additional challenges in diagnosing behind-the-casing flows. To improve measurement accuracy, it is recommended to place temperature sensors above the region affected by natural convection. Additionally, it was found that natural convection induces high-frequency temperature fluctuations in the fluid, which are not detected on the casing surface due to the thermal inertia of the metal. Therefore, for detecting behind-the-casing flows, it is preferable to measure temperature directly on the inner surface of the casing.

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