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Methods of suppressing free thermal convection in water-filled wells during temperature research

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Abstract. Temperature measurements in boreholes are widely used in oil and gas geophysics, hydrogeology, geoecology, geocryology, and in the operation of hydrothermal resources. The number of applications of borehole temperature data is continuously growing. Requirement for temperature measurement accuracy is also growing. However, increasing the accuracy is limited by free thermal convection phenomenon (FTC). It occurs under a positive temperature gradient and causes temperature noise, the level of which may exceed the useful signal.

It was believed for a long time that the FTC currents are organized as a vertical sequence of convective cells having a certain vertical dimension. Existing methods of FTC suppressing by horizontal discs are based on these ideas. Theoretical and experimental studies conducted by the authors showed that these ideas are incorrect. FTC currents are organized as a rotating helical system of ascending and descending jets, not limited vertically. Under these conditions, the most efficient and technological way is dividing the borehole by vertical stripes of polymer film into separate segments. Another method of FTC suppressing uses spherical hydrogel granules. The test results of the developed devices in a real borehole are described. Using of these devices allows to reduce the temperature noise by 16-20 times (from 0.025-0.044 K to 0.002-0.003 K).

Keywords: geothermy, borehole temperature measurements, free thermal convection, temperature monitoring

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Introduction

Temperature studies in wells are used to solve a wide range of problems. In scientific research, thermometry is used to estimate the density of deep heat flow in solving global tectonics problems (Polyak, Khutorskoy, 2018). Temperature monitoring is used to assess geodynamic processes (Shimamura et al., 1985; Demezhko et al., 2012a,b). Thermometry is part of exploration and production-geophysical studies of oil wells to assess the technical condition of wells, to identify intervals of annular cross-flows, flood zones, intervals and profiles of inflow, etc. (Dakhnov, 1982). Temperature measurements are indispensable in hydrogeological (Anderson, 2005; Pehme et al., 2014), geoecological, geocryological studies, and in the exploitation of geothermal water deposits.

In recent years, in connection with the advent of new temperature sensors, distributed measurement systems (including fiber optic), means of recording and transmitting data, the range of thermometry tasks has expanded significantly. There has been a tendency to move from single or occasional temperature measurements to permanent temperature monitoring (Ipatov et al., 2018), methods of active thermometry using a heating cable are being developed (Valiullin et al., 2016; Vélez Márquez et al., 2018; Klepikova et al., 2018). At the same time, the accuracy requirements for temperature measurements are significantly increased. However, hardware accuracy often cannot be implemented in real well conditions due to the influence of free thermal convection (FTC) of liquid or air. The temperature noise caused by unsteady convective flows, in amplitude, can significantly exceed the level of the useful signal.

Obviously, technical devices for suppressing temperature noise, in order to be effective, must take into account the structure of convective flows. The article shows how the ideas about the structure of FTC flows have changed recently and describes the technical devices developed by the authors that can effectively reduce the temperature noise level.

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Conditions under which free thermal convection occurs

In water-filled boreholes FTC occurs with a positive temperature gradient. Its occurrence and character are determined by the value of the dimensionless Rayleigh number. For downhole conditions (vertical cylinder):

$$Ra = \frac{g\beta r^4}{\nu a} G, \tag{1}$$

where g is the gravitational acceleration, β is the coefficient of volumetric thermal expansion, ν is the kinematic viscosity, a is the thermal diffusivity, r is the radius of the well, G is the temperature gradient. The parameters β, ν, a included in this ratio, in turn, depend on temperature. The critical Rayleigh number Ra_{crit}, which determines the occurrence of convection in the well, lies in the range 68-216, depending on the ratio of the thermal conductivities of the fluid filling the well and the surrounding λ_f/λ_m array (Gershuni, Zhukhovitsy, 1972):

$$Ra_{crit} = \frac{96}{5(1+7\lambda_f/\lambda_m)}\Big[3(33+103\lambda_f/\lambda_m) - \sqrt{3(2567+14794\lambda_f/\lambda_m+26927(\lambda_f/\lambda_m)^2}\Big]. \tag{2}$$

For an uncased well (fluid – water, $\lambda_f = 0.6$ W·m^{-1}·K^{-1} at 20 °C, external array – rocks, $\lambda_m = 2.5$ W·m^{-1}·K^{-1}), $Ra_{crit} = 154$, for cased (steel casing, $\lambda_m = 74$ W·m^{-1}·K^{-1}), $Ra_{crit} = 212$.

It can be seen from (1) that in order to reduce the Rayleigh number below a critical level, it is necessary to reduce the characteristic size, in this case, the internal radius of the well.

Conventional views about the structure of FTC flows and methods for its suppression

Conventional methods of controlling FTC are based on ideas about the structure of convective currents that developed in the middle of the last century. According to these ideas (Van der Merwe, 1951; Diment, Urban, 1983; Cermak et al., 2008; Berthold, Börner, 2008), FTC flows are organized in the form of a vertical sequence of convective cells (similar to Rayleigh-Benard cells in a flat layer), having a certain vertical size (Fig. 1a-c), which, in turn, determines the amplitude of the temperature noise.

Based on these ideas, all well-known technical means of suppressing convection in a well have been created. They divide the well vertically into separate intervals using packers (Beck et al., 1971; Colombani et al., 2016) (Fig. 1e-f) or horizontal disks (Harries, Ritchie, 1981; Vroblesky et al., 2006; Vélez Márquez et al., 2018) (Fig. 1d-e). It was assumed that for effective suppression of convection this interval should be less than the vertical size of the convective cell. However, the size is not known: until now no convincing estimates have been submitted. The use of packers is very time-consuming, and the effectiveness of dividing disks is recognized as low (Pavlov, 2006).

More radical methods for solving the problem are also known. I.L. Dvorkin et al. (1981) propose lowering the tubing string into the interval under study, which effectively reduces the effective radius and, consequently, the Rayleigh number. The disadvantage of this method is the high cost of research and high complexity. In (GOST 25358-82. Soils. Field Temperature Method, 1982), for suppressing free thermal convection of air in shallow (up to 5 m) wells with a diameter of more than 100 mm, it is prescribed, after installing sensors, to fill the entire well with sand or fine gravel, and in (Klepikova et al., 2018) water-filled wells with dry hydrogel. The disadvantages of these methods are obvious, and in deeper wells they are simply not applicable.

Modern concepts and methods of suppressing FTC

Theoretical and experimental studies of free thermal convection in a well (Mindubaev, Demezhko, 2012; Khoroshev, 2012; Demezhko et al., 2017, 2019) showed that FTC flows form a rotating spiral system of ascending and descending jets and are not limited vertically (Fig. 2).

Taking into account the revealed structural features of the FTC, we developed an effective method of suppressing the FTC, based on dividing the well by vertical stripes from a polymer film into separate segments. Such a separation, on the one hand, reduces the effective section of the well and the Rayleigh number, on the other hand, prevents the possibility of the system rotation (Khatskevich et al., 2019). Possible implementations of this method are shown in Fig. 3a-b.

Methods based on filling a well with bulk material (GOST 25358-82. Soils. Field Temperature Method, 1982; Klepikova et al., 2018) are quite effective in conducting long-term temperature monitoring, but are not technologically advanced. They are suitable only for shallow wells and make it difficult, if not completely excluded, to re-monitor, for example, after calibration. We have developed a method based on filling only a limited portion of the well (monitoring interval) with spherical hydrogel granules (Khatskevich, Demezhko, 2019)(Fig. 3c-d). Before installing temperature sensors in the well, a cylindrical sleeve of a stretching polymer mesh is attached to the cablewith spherical hydrogel granules placed in it. Within several hours after the sensors are installed in the well, spherical granules swell and increase in size by 30-100 times, stretching the grid, until they fill the entire space of the well within the studied interval. Since the dimensions of the free space are smaller than the radius of spherical granules, thermal convection is completely suppressed even in the

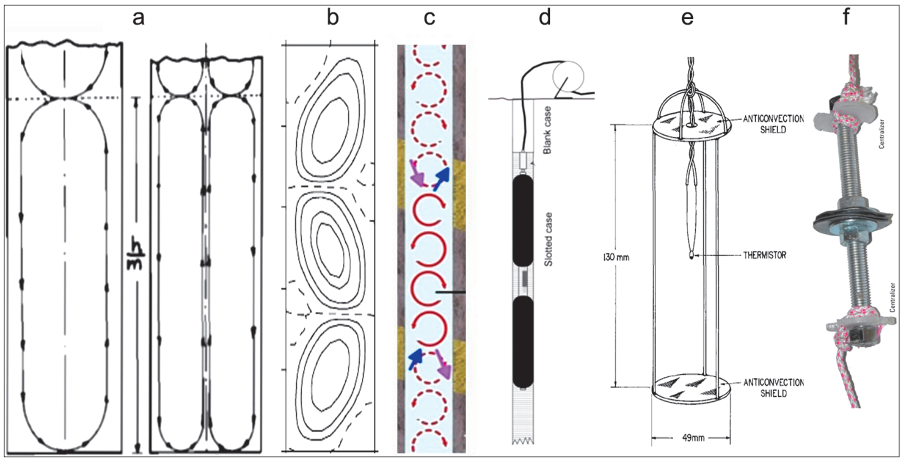

Fig. 1: Conventional views on the structure of FTC flows (a-c) and methods for suppressing it (d-f): a – Van der Merwe, 1951; b – Cermak et al., 2008; c – Berthold, Borner, 2008; d – a device for suppressing FTC using packers – Colombani et al., 2016; e-f – using horizontal disks: (e) – Harries, Ritchie, 1981; (f) – Vroblesky et al., 2006.

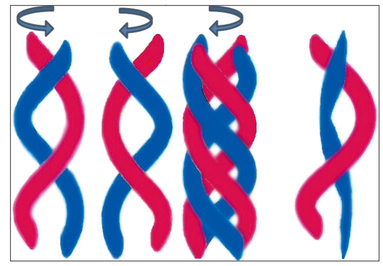

Fig. 2. Spiral systems of ascending (highlighted in red) and descending (blue) flows of free thermal convection. Black arrows indicate the direction of the system rotation (Demezhko et al., 2019)

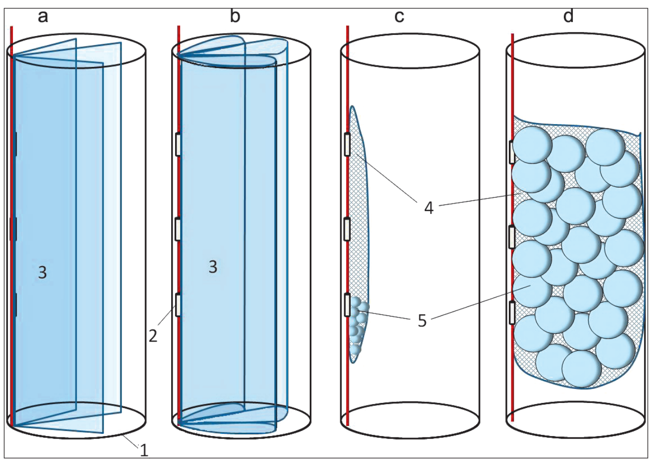

Fig. 3. Methods of suppressing FTC in a well: a, b – two options for implementing the method using polymer film strips (Khatskevich et al., 2019); c, d – using a hydrogel (Khatskevich, Demezhko, 2019). The location of the hydrogel granules immediately after installing the cable with the sensors in the monitoring interval (c) and a few hours after swelling of the granules (d). 1 – well, 2 – cable with sensors, 3 – polymer film, 4 – sleeve of polymer mesh, 5 – spherical hydrogel granules.

case of large Rayleigh numbers (10^5-10^8). At the same time, the densest packing of spheres (face-centered cubic and hexagonal) preserves the porosity e = 0.26, and with arbitrary packing it increases to e = 0.48. This allows vertical movements of the liquid column in the well. When removing the cable after monitoring, the sleeve from the polymer network breaks and the granules are lowered into the well sump.

Test results

Tests for FTC suppression devices were tested in an IGF-60 well 60 m deep drilled in 2007 at the Institute of Geophysics of the Ural Branch of the Russian Academy of Sciences (Yekaterinburg). To a depth of 43 m, the well is cased with steel pipes: in the range of 0.3-27.0 m – Ø 114 mm (internal Ø 105 mm), in the range of 27-43 m – Ø 108 mm. Below, to a depth of 60 m, there is an open trunk Ø 93 mm. The well revealed a soil layer (0-0.3 m), loam (0.03-10.0 m), fractured (10.0-43.0 m) and durable (43.0-60.0) gabbro. The groundwater level in the well was established at a depth of 5.9-6.5 m.

Temperature monitoring was carried out during the period from November 6, 2008, to October 10, 2009 using an autonomous digital 16-channel temperature meter (AIT) developed at the Trofimuk Institute of Petroleum Geology and Geophysics of the Siberian Branch of the Russian Academy of Sciences (Kazantsev, Duchkov, 1992). MMT-4 thermistors were used as temperature sensors. 6 temperature sensors were installed in the IGF-60 well at depths of 10, 20, 30, 40, 50, 60 m (below groundwater level), 4 sensors – in a 4.5-meter hole located a meter from it, into which a closed hole was inserted from the lower end and water-filled steel pipe Ø 32 mm (internal Ø 29 mm) at depths of 1, 2, 3, 4.38 m, 3 sensors were located in the soil at depths of 0.2; 0.3; 0.5 m. The monitoring results to a depth of 10 m are presented in Fig. 4. Below this mark, the temperature field practically did not change during the year, and the temperature gradient was close to zero.

In the annual cycle, a positive temperature gradient (0.08-0.22 K/m) is observed in the flooded part of the well at a depth of 6-10 m at the end of May, in June. At $T = 5°C$, the constants included in (1) are equal for water: $\beta = 1.54 \cdot 10^{-5}$ K^{-1}, $\nu = 1.54 \cdot 10^{-6}$ m^2/s, $a = 1.32 \cdot 10^{-7}$ m^2/s and the Rayleigh numbers corresponding to temperature gradients are Ra = 450-1200. The critical value for cased steel pipe well, according to (2) Ra_{cr}, is 212. Therefore, during this period, developed free thermal convection can be expected in this interval.

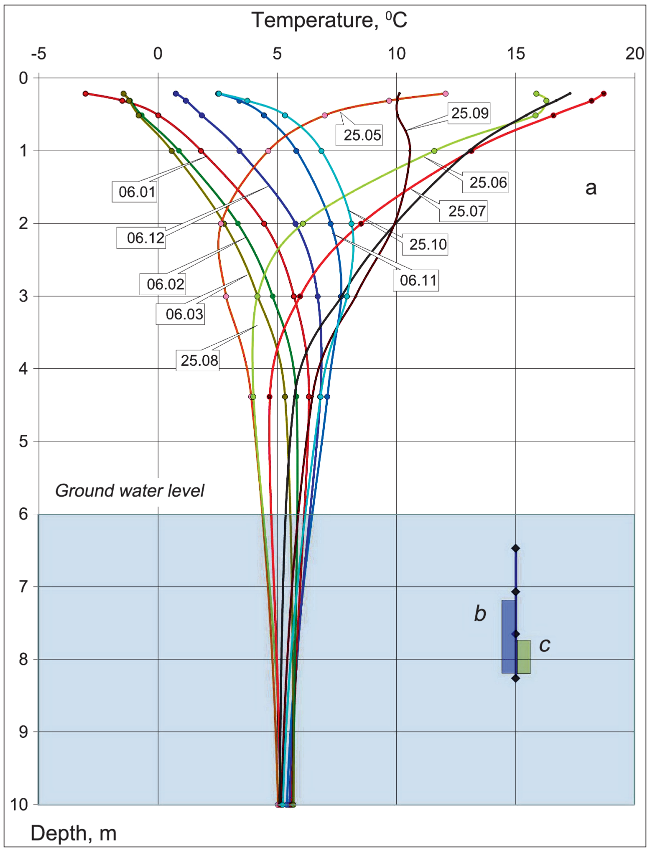

Fig. 4. Results of temperature monitoring in the IGF-60 well in November 2008 – October 2009 (a) and intervals for installing temperature sensors and FTC suppressors: b – vertical plates, c – grids with hydrogel

Tests of the FTC suppressor device using vertical plates were tested in late May – early June 2019. At the first stage, temperature was monitored for a week at depths of 6.47, 7.07, 7.65, and 8.26 m with a sampling frequency 30 sec. Then the sensor string was removed and equipped with an FTC suppression device consisting of folded strips of a polyethylene film 1 m long (Fig. 3b, Fig. 5 – photo). The middle of the device was located at the sensor 7.65 m, so the neighboring sensors were not blocked by it (Fig. 4b). After this, monitoring continued for another 5 days. Thermograms of the results of monitoring and evaluation of temperature noise are shown in Fig. 5 and Tab. 1.

Under conditions of free thermal convection, the amplitude of temperature noise is σ = 26-44 mK. After installing the device after about 1.5 days, it decreases by 6-22 times – to σ_p = 2-4 mK. The maximum suppression coefficient $k = \sigma/\sigma_p$, naturally, appears at a depth of

Depth, m	6.47	7.07	7.65	8.26
Before suppression, σ, K	0.0271	0.0409	0.0440	0.0262
After suppression, σ_p, K	0.0044	0.0021	0.0020	0.0019
Suppression coefficient, $k=\sigma/\sigma_p$	6.1	19.2	21.8	13.5

Table 1. Amplitudes of temperature noise (standard deviations of residuals from smoothing thermograms with a 6-hour filter) in the IGF-60 well before and after FTC suppression using vertical plates

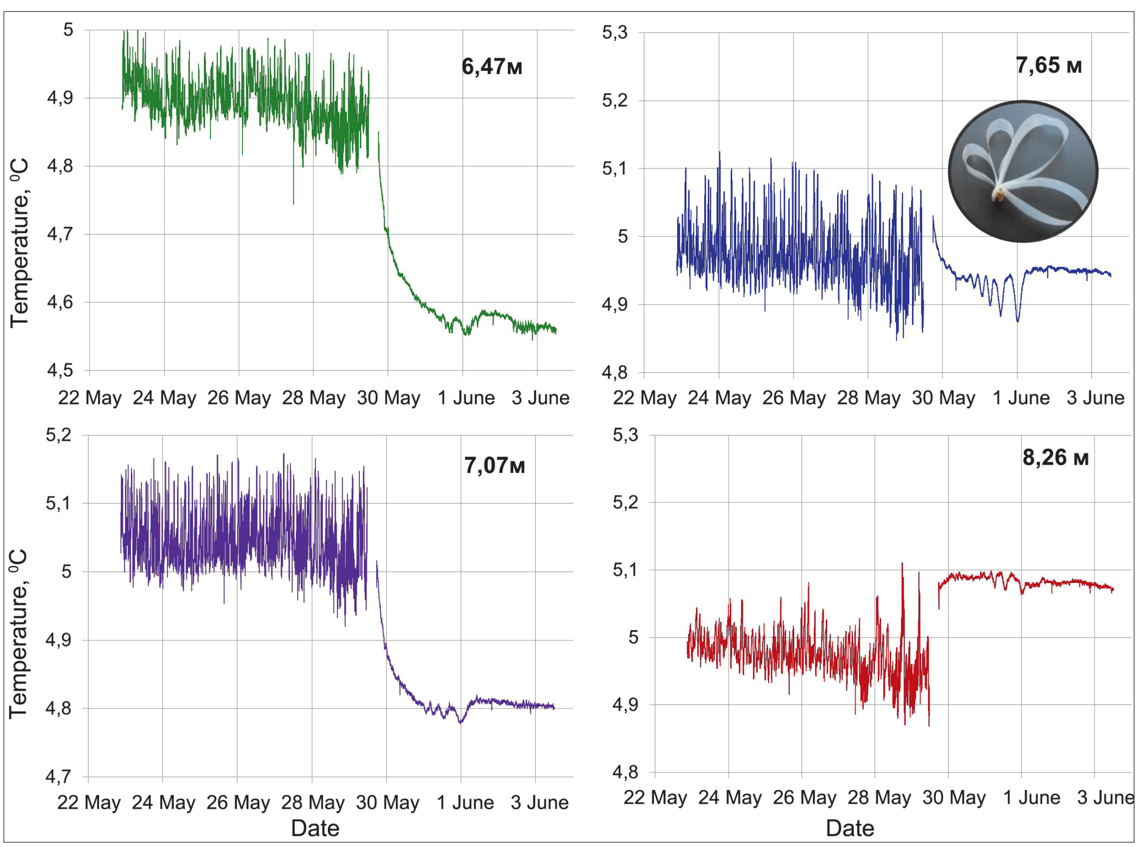

Fig. 5. The results of temperature monitoring in the IGF-60 well during testing of an FTC suppression device based on vertical plates. A sectional photo of the deviceis in the upper right corner.

7.65 m – in the area covered by the FTC suppression device. However, beyond the boundaries of the overlapped interval, the temperature noise decreases to 2 mK, and at a depth of 6.47 m (0.68 m from the upper edge of the device) to 4 mK.

Interestingly, after the installing the device in its middle part (7.65 m), temperature fluctuations occurred for about 1.5 days, the range of which reached 70 mK, and the period increased from 5 to 10 hours. These fluctuations, but with a smaller scale, were recorded by neighboring sensors. Their nature is not clear to us. We can only assume the appearance of a self-oscillating system in the process of heat exchange between the device and the surrounding fluid. Similar temperature self-oscillations were observed by us earlier (Demezhko, Yurkov, 2017) – they appeared and continued (with a period of 14-26 hours and a span of up to 300 mK) for several months, and then suddenly disappeared. At the same time, no additional devices were introduced into the well.

Figure 6 shows the amplitude spectra of temperature fluctuations at a depth of 7.65 m before and after installing the FTC suppression device. Free thermal convection is most pronounced in the range of periods 5-140 min. It is in this range that its most effective suppression occurs. Non-convective factors make a significant contribution to fluctuations with periods of more than 12 hours, for example, those associated with fluctuations in temperature and atmospheric pressure, and precipitation.

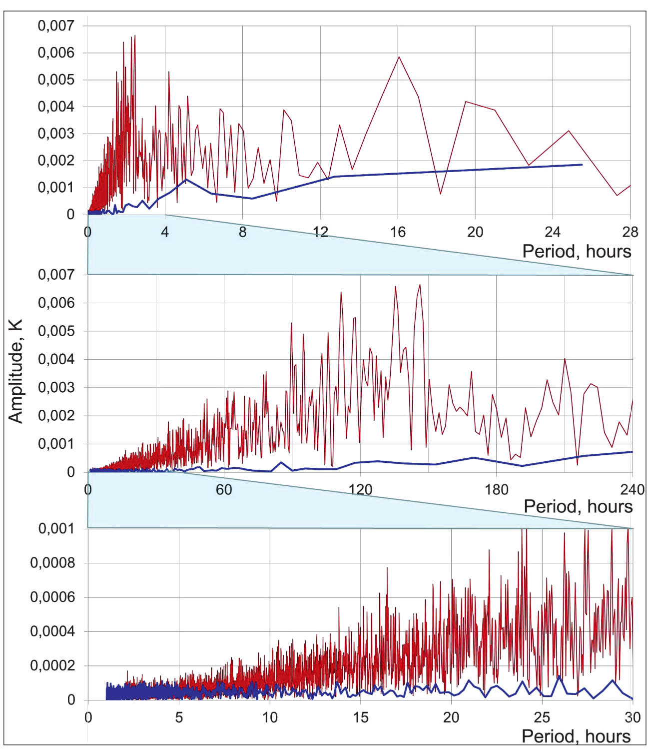

Fig. 6. Spectral composition of temperature noise without convection suppression (red) and after suppression (blue)

Here the amplitudes before and after the installation of the device are comparable. They are also comparable for periods of less than 5 minutes – in this range temperature fluctuations are already associated with instrument noise.

In addition to temperature noise – fluctuations relative to the average value for a given depth – free thermal convection causes a long-term, or quasi-stationary, effect (Demezhko et al., 2017). It is expressed in a regular decrease in the temperature gradient at the convection development site and is similar to the effect of forced convection, for example, during circulation of well fluid during drilling or flushing a well (Astrakhan, Maron, 1969; Cheremensky, 1977; Sass et al., 1992). Mathematical modeling (Demezhko et al., 2017) showed that the maximum decrease in the gradient in the well compared with the gradient in the surrounding rocks is observed at the upper and lower boundaries of the well, while in the middle part it remains close to the rock. Significant distortions of the average rock temperatures were noted just during measurements in shallow wells (Pavlov, 2006, and references in this work).

In our case, the measurements were carried out in the upper part of the well, near the water/air interface, and here we should also expect the manifestation of the quasistationary thermal effect of convection. Figure 5 shows that after installing the FTC suppression device, the temperature profiles diverge: the sensors installed above the device detect a decrease in temperature, lower – an increase, and the sensor located in the middle of the device at a depth of 7.65 m does not change the temperature trend. In Fig. 7a shows

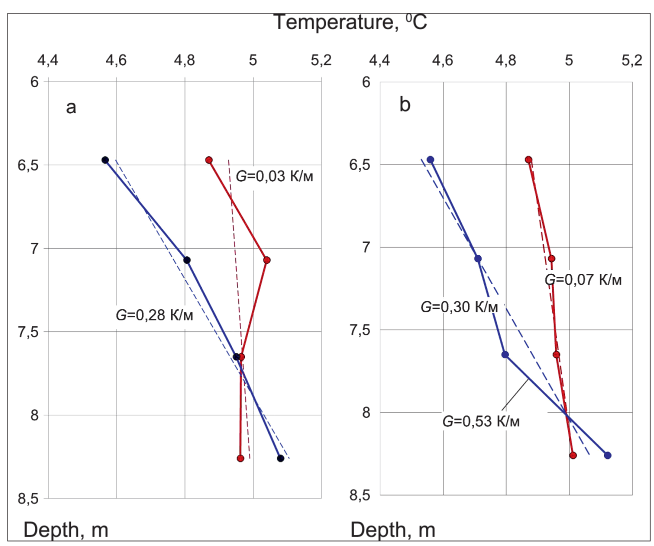

Fig. 7. Temperature profiles recorded in the IGF-60 well before (red lines) and after (blue lines) the installation of FTC suppression devices: a – graphs for the device in the form of vertical plates, b – for the hydrogel-based device. Dotted line indicates linear approximations of profiles.

averaged vertical temperature profiles recorded in the IGF-60 well before and after installation of the FTC suppression device. Under the conditions of developed convection, the average measured temperature gradient was 0.03 K/m, and after suppressing convection, it increased to 0.28 K/m – i.e. to its real value in the rocks. At T = 4.9 °C, this gradient corresponds to Ra = 1400. Let us note that with an average gradient of 0.03 K/m (Ra = 150), convection should not have occurred.

To prove that the suppression of the FTC using the device in question made it possible to evaluate the real geothermal gradient, we consider the relationship between the amplitude of the temperature noise and the gradient. We proposed this $\sigma/r \approx 3G$ dependence based on the results of mathematical modeling of the FTC (Demezhko et al., 2017) and confirmed by laboratory experiments (Demezhko et al., 2019). It follows from it that $G \approx \sigma/3r$. In this example (for a depth of 7.65 m) σ = 0,044 K, r = 0,0525 m, which corresponds to a value of G = 0.28 K/m, exactly equal to the gradient measured after suppression of the FTC. True, estimates from neighboring sensors will no longer be as accurate: 0.26 K/m (7.07 m) and 0.17 K/m (8.26 m). Thus, even without convection suppression, by measuring only the temperature noise induced by it, we can try to estimate the temperature gradient not disturbed by convection, or at least to assume that it is significantly distorted.

The test procedure for the device for suppressing FTC using a hydrogel is similar to that described above. The tests were carried out in mid-June 2019. After two-day temperature monitoring at depths of 6.47, 7.07, 7.65 and 8.26 m (sampling frequency – 1 min.) in the interval 7.75-8.15 m on a separate suspension, a device was installed – a 0.4-meter sleeve made of polyethylene mesh, filled with spherical hydrogel granules. Since the initial granule size (approx. 2 mm) was smaller than the cell size (5 mm), the granules were placed inside a sleeve in a small cylinder of permeable fabric. As the granules swell and increase in size (up to 10-12 mm), they fall into the sleeve, gradually filling the entire space of the well in the range of 7.75-8.15 m. After this, monitoring continued for about 6 days. Note that in this experiment, none of the sensors was blocked by the device (Fig. 4c). Thermograms of the results of monitoring and evaluation of temperature noise are shown in Fig. 8 and Table 2.

Under conditions of free thermal convection, the amplitude of temperature noise was σ = 25-38 mK. The device allowed to reduce noise 10-17 times near its installation (sensors "7.65 m" and "8.26 m") and up to 3-6 times – at a distance (sensors "6.47 m" and "7.07 m"). It is noteworthy that the greatest residual noise was registered not by the sensor farthest from the installation, but by the intermediate one – "7.07 m". When convection was suppressed by hydrogel, a transient self-oscillation process was not observed.

As in previous tests, after installing the device, the average temperature gradient over the entire interval increased significantly (Fig. 7b): from 0.07 to 0.30 K/m (Ra = 1500 at T = 4.9 °C), and directly in the installation interval of the device – up to 0.53 K/m (Ra = 2700 at T = 4.9 °C).

Depth, m	6.47	7.07	7.65	8.26
Before suppression, σ, K	0.0253	0.0315	0.0362	0.0375
After suppression, σ_p, K	0.0044	0.0119	0.0034	0.0023
Suppression coefficient, $k=\sigma/\sigma_p$	5.8	2.6	10.8	16.3

Table 2. Amplitudes of temperature noise (standard deviations of residuals from smoothing thermograms with a 6-hour filter) in the IGF-60 well before and after FTC suppression using a hydrogel.

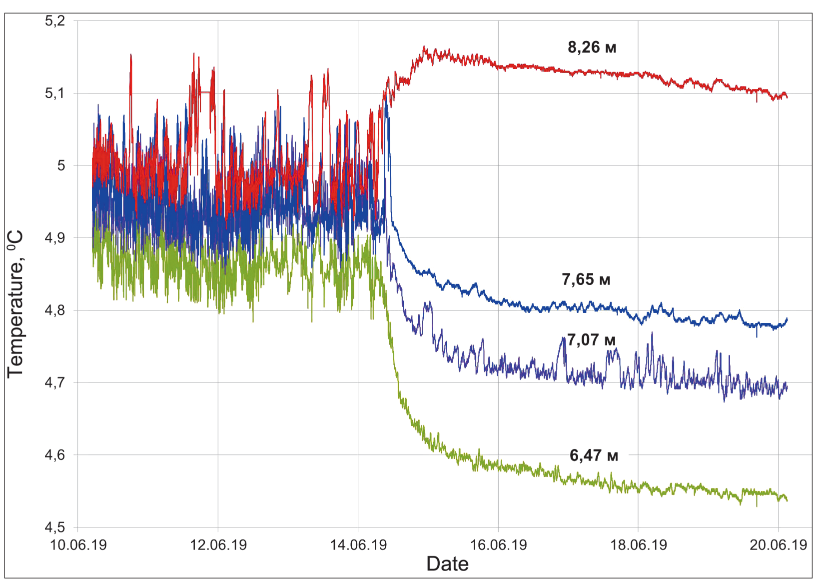

Fig. 8. The results of temperature monitoring in the IGF-60 well during testing of a hydrogel-based FTC suppression device

Conclusion

The latest ideas about the structure of flows of free thermal convection, obtained on the basis of theoretical and experimental studies, have allowed the development of effective and technological methods and devices for its suppression and increase the accuracy of temperature studies in wells. Tests have shown that they can reduce temperature noise by 16-20 times (to 0.002-0.003 K) – to the hardware level. Installed in the well, these devices do not limit the vertical movements of the liquid column associated with changes in atmospheric pressure, tidal deformations, and activation of hydrogeological processes – movements that can be considered as a useful signal. The designs of the developed devices are cheap, easy to implement, exclude the seizure of downhole tools, and allow repeated studies in shallow wells.

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