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Application of Fiber Optic Thermometry Monitoring in the Control the Formation of Cement Stone in the Well Annulus

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Применение оптоволоконного мониторинга термометрии при контроле формирования цементного камня в затрубном пространстве скважин

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A promising method for monitoring the process of waiting for cement hardening in wells is the use of fiber optic well thermometry or distributed temperature sensing (DTS). The DTS method creates the opportunity to move from post-facto measurements to real-time monitoring with the identification of complicated areas and timely adoption of the necessary design decisions. As a result of the research, the technology for thermometric monitoring of the process of cement stone formation was developed. The purpose of the work was to determine the applicability of practical skills developed over more than 10 years in the field of production geophysical research using the DTS method to solve the applied problem of well construction. It was established that the data obtained from DTS, in addition to solving applied problems (determining the reaction temperature, data on the result of cementing, etc.), made it possible to solve the problems of monitoring the processes occurring in the annulus during the formation of cement stone and create a platform for the further development of technologies for rapid response to identified complicated areas. The results of the work performed can be widely used in monitoring the well construction process, and are also of interest from the point of view of further development, both from a technological point of view and methodologically.

Ключевые слова:
оптоволоконный мониторинг, оптоволоконные системы, затрубное пространство скважин, контроль цементирования, распределенное температурное зондирование, ожидание затвердевания цемента.

Перспективным при контроле процесса ожидания затвердевания цемента в скважинах является применение оптоволоконной термометрии скважин (DTS). Метод DTS создает возможность перейти от замеров постфактум к мониторингу в режиме реального времени с выявлением осложненных участков и своевременному принятию необходимых проектных решений. В результате проведенных исследований отработана технология проведения термометрического мониторинга процесса формирования цементного камня. Целью работы является определение применимости наработанных за более чем 10 лет практических навыков в области промыслово-геофизических исследований методом DTS для решения прикладной задачи строительства скважины. Установлено, что полученные по DTS данные, помимо решения прикладных задач (определение температуры реакции, данные о результате цементирования и пр.), позволяют решить задачи контроля процессов, происходящих в затрубном пространстве при формировании цементного камня и создают платформу для дальнейшего развития технологий оперативного реагирования на выявленные осложненные зоны. Результаты выполненной работы могут получить широкое применение при контроле за процессом строительства скважин, а также представляют интерес с точки зрения дальнейшего развития направления как с технологической точки зрения, так и методологически.

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Introduction

Currently, one of the most promising areas for monitoring the operation of oil and gas production wells is application of fiber optic technologies. The main advantage of using fiber optic monitoring is the ability to carry out continuous monitoring along the entire length of the well recording events in real time [1, 2]. Fiber optic technologies for well monitoring have been increasingly used in recent years both abroad [3–5] and in the domestic oil and gas industry [6–8]. At the same time, a promising method for monitoring development is monitoring the distribution of the temperature field along the wellbore [9, 10]. In a modification of temperature measurement at wells fiber-optic well thermometry (distributed temperature sensing – DTS) is used [11, 12]. In the Perm region in the period 2012–2024 there are results of the successful using DTS technology in monitoring development in terms of identifying zones of column leakage and annulus flows [13–15]; identifying anomalies associated with the separation of the liquid phase composition [16–18]; monitoring the operating technological equipment [19].

One of the urgent tasks of well operation is monitoring the wells technical condition including controling the process of waiting on cement hardening (WOC) [20–22]. To date, studies to determine the quality of casing cementation are being carried out direct measurement of the parameters of the cement injection process [23], as well as after completion of the WCC using standard methods of cement bond logging (ACBL) and gamma-gamma cement bond logging (GG-c) [24–26]. If intervals of cement absence as well as contact of cement with rock or the column are identified, additional operations to refill cement through specially created technological holes are carried out [25]. It should be noted that in recent years with the development of systems for processing geophysical material [27–29], as well as the introduction of CBL scanning modifications [30, 31], the quality level of the performed measurements has significantly increased. However, in generally performing the operations described above leads to an increase in the time for constructing a well and, accordingly, to a significant increase in its cost. In addition, standard methods do not allow a detailed description of the defect types in the cement ring. In the authors' opinion, this problem can be solved more effectively and at a lower cost by using fiber wells optic thermometry. At the same time, measurements based on fiber optic thermometry technology (DTS) can be implemented both in the conductor and in the technical string of a well under construction. In general, this creates the opportunity to move from post-facto measurements to real-time monitoring [32–34] with the identification of complicated sites and timely adoption of necessary design decisions. In particular, the use of DTS-based monitoring makes it possible to complete the WOC process not according to the average time interval included in the well construction plan but precisely at the actual completion of the cement setting process which reduces the risks of construction and subsequent operation of the well.

Modern DTS recording systems allow simultaneous measurements on five fiber optic lines. While implementing method, it was used the Silixa Ultima-S recorder which is a small-sized measuring complex that allows measurements of the required quality level to solve thermometry problems [9], the technical characteristics are given in the table which provides the ability to measure temperature along the length of a fiber optic cable with a step of 25 cm and accuracy up to 0.05 degrees.

Technical characteristics of the measuring thermometry complex Silixa Ultima-S

Parameter	Silixa Ultima-S
Discretization interval, cm	12,5
Sampling resolution, cm	25
Temperature resolution, ˚C	0,01
Measuring time, c	From 1
Responsivity, ˚C	0,05
Cable length, km	Up to 5
Lenth resolution, cm	12
Time Storage time, min	12

Research Objectives. Materials and Methods

A specialized cable in a reinforced sheath is used as a sensor which prevents damage to the fiber during round-trip process and also allows the cable to be operated on a standard geophysical logging self-propelled hoist. Moreover, instead of the standard cable design (conductive cores and polymer insulation) four fiber threads are used which are direct temperature sensors placed in a gel-filled steel tube. The design uses two layers of cable armor, which ensures a maximum tensile load of 55 kN.

To control the recorded absolute values the complex geophysical device "Sova-5" was used which allows for simultaneous measurement of temperature, pressure and also the exposure dose rate of rocks gamma ray (GR) for reference to the well section. The device has a valid calibration certificate; during the measurement process it was placed at the lowest point of the geophysical cable at a depth of 971 m.

To carry out pilot work for controling the hardening of cement stone, a well was selected that operates an object at one of the deposits within the boundaries of the Verkhnekamskoye potassium salt deposit (VKPSD). The joint development of oil and potassium salt reserves significantly increases the requirements for monitoring the quality of well casing [35–37] which makes the task set for this territory even more relevant.

Results

Research to control the hardening of cement stone using fiber-optic thermometry as part of pilot work was carried out at one of the wells of LUKOIL-PERM LLC.

While performing the work, the following tasks were set:

– to determine the possibility of controlling the cement setting process using a fiber optic cable;

– to determine the time required for complete hardening of the cement stone for subsequent support quality control.

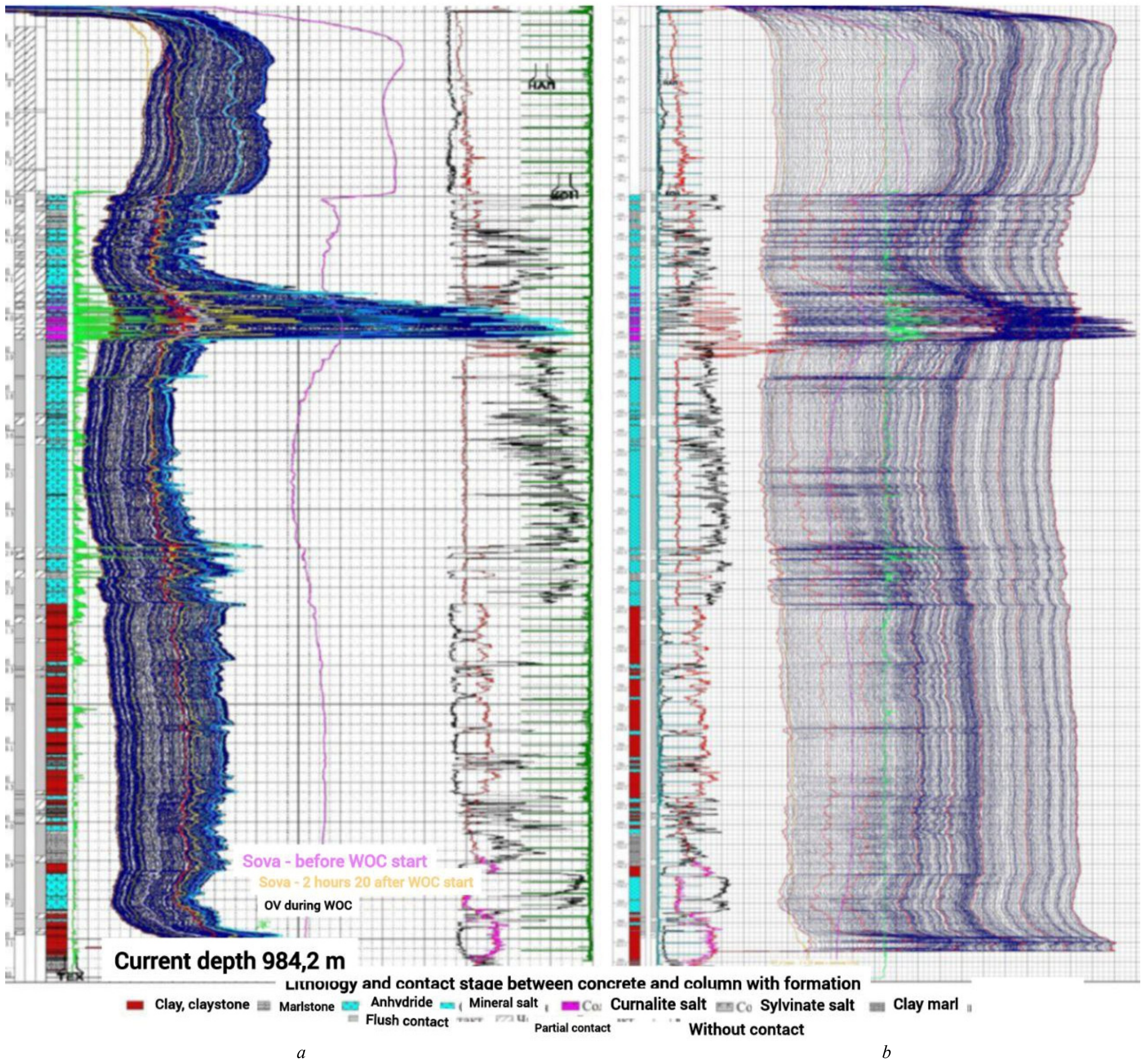

Fig. 1. Monitoring the WOC of a technical column using fiber-optic thermometry (*a*); Controlling WOC of the technical column using fiber-optic thermometry (sweep) (*b*)

In the process of research, fiber optic cable was lowered into the well after cementing the technical casing (*d* = 245 mm), the first recording was made 4 hours after the completing cement pumping. The recordings lasted 44 hours in increments of 12 min (accumulation time).

Preliminarily, in order to increase the reliability of the data and eliminate ambiguities in interpretation during the well construction process (in an open hole) a logging set was carried out for the purpose of lithological subdivision of the section, the data was plotted on tablets (Fig. 1, 2). After completion of the monitoring it was carried out recording using acoustic (ACBL) and gamma-gamma cement bond logging (GG-c) methods, the result was plotted on tablets (see Fig. 1, 2). One of the possible ways to improve technology can be the using formation testing the inflow [38-40] which will allow to obtain the most reliable information about rocks saturation in the target interval. In this case, these methods were not used due to the technological features of the well operating mode.

During the research the following recordings were made: background measurements using the complex geophysical device “Sova-5” and thermometry measurements during the time of technical column WOC. As a result of the interpreting a fiber-optic thermometry studies complex, the following practical conclusions were obtained:

– the position of the current face after cementing is determined at a depth of 984.2 m (see Fig. 1, a);

– cement lifting to the wellhead was established (see Fig. 1, *b*);

– after cementation, thermodynamic processes are observed throughout the wellbore. The most intense heating was noted in the interval of the carnalite sequence of the Irensky horizon; the maximum heating temperature was 50.6 °C (see Fig. 1).

At the same time, an analysing the dynamics of temperature changes shows that at a depth of 971 m the temperature increased from 24.7 to 29.5 °C, then gradually decreased and at the end of the measurement it was 22.0 °C. The pressure did not change and was about 125.6 atm (Fig. 2).

In the first day, an intense reaction occurs with the heat release, the function is exponential in nature, and specifically due to heat transfer to the environment. After a day the potential of the exothermic reaction drops, the reaction slows down - the temperature decreases according to a linear law due to heat transfer to the environment. It has been established that in the interval of a two-column structure the process goes on more slowly than behind a single column. This occures probably due to heat transfer and/or cement hydration processes. It is expected that when the reaction stops, the process of equalizing the temperature with the environment will take the hyperbolic form. In this case we can talk about the end of the hardening process in the cement stone. Due to limited recording time the temperature reached an asymptote during the work was not recorded.

Since the fiber optic cable is directly a temperature sensor, at each wellbore point with a sampling step (see table) it is possible to plot the temperature distribution over time.

In this case, unlike a standard geophysical instrument with a temperature sensor (Fig. 2), there is no need for cable movement in the well. This allows you to study the dynamics of rapidly changing well events without the risk of data loss.

Conclusion

As a result of the research carried out using DTS, the technology was developed and the process of cement stone formation was monitored. The obtained results make it possible to record temperature online, in contrast to standard methods for measuring ACBL and GG-c. As a result, it was found that the planned stated cement hardening time is not enough to complete the reaction which indicates incomplete cement formation stone at the time of measuring ACBL and GG-c Analysing the obtained results suggests that there is high potential for further development of the proposed technology, including its methodological development, as well as development through automation of technological processes. An important advantage of the DTS method is the future possibility to place a fiber optic cable behind the column directly in the cement which makes it possible to organize a long-term monitoring system both during and after completion of the well construction.

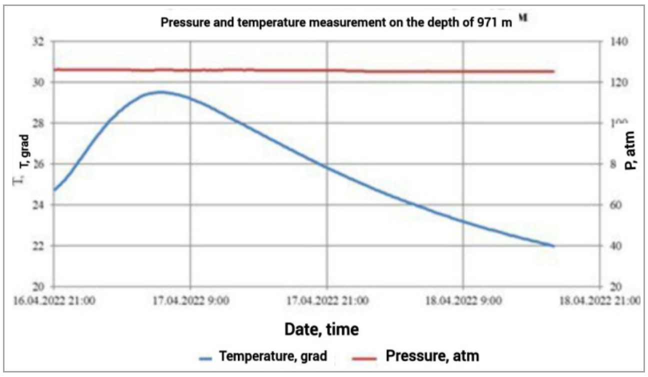

Fig. 2. Temperature and pressure distribution in time at the bottom using the “Sova-5” device

A promising direction for solving these problems seems to be the integrating DTS with the technology of distributed acoustic sensing (DAS) [41–43], which will allow us to speak more reliably about the nature of the identified temperature anomalies. It is advisable to monitor well performance using DTS and DAS methods simultaneously with a unified recording system that allows synchronizing their results.

References

1. Kislov K.V., Gravirov V.V. Raspredelennoe akusticheskoe zondirovanie: novyi instrument ili novaia paradigma [Distributed Acoustic Sensing: A New Tool or a New Paradigm]. *Seismicheskie pribory*, 2022, vol. 58, no. 2, pp. 5-38. DOI: 10.21455/si2022.2-1

2. Kruiver P., Obando-Hernández E., Pefkos M., Karaoulis M., Bakx W., Doornenbal P., Ciocca F., Chalari A., Mondanos M. Fibre Optic Monitoring of Groundwater Flow in a Drinking Water Extraction Well Field: Conference Proceedings, First EAGE Workshop on Fibre Optic Sensing. Amsterdam, 9-11 March 2020. Amsterdam, 2020. DOI: 10.3997/2214-4609.202030010

3. Zeinab Movahedzadeh, Alireza Rangriz Shokri, Rick Chalaturnyk, Erik Nickel, Norm Sacuta. Measurement, monitoring, verification and modelling at the Aquistore CO_2 storage site. *FIRST BRAKE*, 2021, vol. 39, pp. 69-75. DOI: 10.3997/1365-2397.fb2021013

4. Alumbaugh David L., Evan Schankee Um, Hoversten G. Michael, Key Kerry. Distributed electric field sensing using fibre optics in borehole environments. *Geophysical Prospecting*, 2022, vol. 70, pp. 210-221. DOI: 10.1111/1365-2478.13150

5. Peyman Moradi, Suresh Dande, Doug Angus. Fibre-optic sensing and microseismic monitoring evaluate and enhance hydraulic fracturing via real-time and post-treatment analysis. *FIRST BRAKE*, 2020, vol. 38, pp. 65-72. DOI: 10.3997/1365-2397.fb2020067

6. Kuvshinov B.N. Interaction of helically wound fibre-optic cables with plane seismic waves. *Geophysical Prospecting*, 2016, vol. 64, no. 3, pp. 671-688. DOI: 10.1111/1365-2478.12303

7. Kolychev I.Iu., Denisov A.M., Belov S.V. et al. Otsenka vozmozhnostei primeneniia tekhnologii vibroakusticheskogo vozdeistviia (DAS) pri monitoringe raboty neftianykh i gazovykh skvazhin [Assessment of the possibilities of using distributed acoustic sensing technology in monitoring the operation of oil and gas wells]. *Problemy razrabotki mestorozhdenii uglevodorodnykh i rudnykh poleznykh iskopaemykh*, 2022, vol. 1, pp. 250-255.

8. Chugaev A.V., Tarantin M.V. Amplitudno-chastotnyi otklik raspredelennogo akusticheskogo sensora DAS so spiral'noi namotkoi volokna [Amplitude-frequency response of a helically-wound fiber distributed acoustic sensor]. *Gornye nauki i tekhnologii*, 2023, vol. 8, no. 1, pp. 13-21. DOI: 10.17073/2500-0632-2022-06-10

9. Chekaliuk E.B. Termodinamika neftianogo plasta [Thermodynamics of an oil reservoir]. Moscow: Nedra, 1965.

10. Naidanova E.S., Rybka V.F., Gubina A.I., Chudinov P.Iu. Monitoring temperaturnogo polia s pomoshch'iu optovolokonnykh tekhnologii pri ploshchadnykh issledovaniiakh [Temperature field monitoring with the help of fiber optic technologies in areal surveys]. *Karotazhnik*, 2020, no. 6 (306), pp. 82-91.

11. Lee D., Park K.G., Lee C.-N., Choi S.-J. Distributed Temperature Sensing Monitoring of Well Completion Processes in a CO_2 Geological Storage Demonstration Site. *Sensors, Basel*, 2018, vol. 18, 4239 p. DOI: 10.3390/s18124239

12. Lauber T., Lees G. Enhanced Temperature Measurement Performance: Fusing DTS and das Results. *IEEE Sensors Journal*, 2021, vol. 21, no 6, pp. 7948-7953. DOI: 10.1109/JSEN.2020.3046339

13. Naidanova E.S., Rybka V.F., Chudinov P.Iu. Opyt ispol'zovaniia optovolokonnykh tekhnologii pri geofizicheskikh issledovaniiakh skvazhin [An experience of using fiber optic technologies in well logging]. *Karotazhnik*, 2019, no. 5 (299), pp. 62-72.

14. Shiriaev E.O. Opyt primeneniia optovolokonnykh sistem termometrii dlia issledovaniia skvazhin [An experience of applying fiber-optic temperature-measurement systems for well logging]. *Karotazhnik*, 2023, no. 6 (326), pp. 76-86.

15. Chudinov P.Iu. Opredelenie debita skvazhin i uchet dobychi s ispol'zovaniem optovolokonnykh tekhnologii [Well output evaluation and production monitoring using fiberoptic technologies]. *Karotazhnik*, 2023, no. 6 (326), pp. 87-96.

16. Rybka V.F. Rezul'tat primeneniia optovolokonnykh tekhnologii raspredelennoi termometrii pri osvoenii skvazhiny s pomoshch'iu ETsN [The result of the application of distributed fiber-optic technology in thermometry of development wells with ESP]. *Ekspozitsiia neft' gaz*, 2013, no. 7 (32), pp. 13-16.

17. Rybka V.F., Vasiutinskaia S.I. Volokonno-opticheskaia termometriia skvazhin. Monitoring formirovaniia gazogidratnoi probki [Fiber-optic thermometry of wells. Monitoring the formation of gas hydrate plug]. *Nauchnyi zhurnal Rossiiskogo gazovogo obshchestva*, 2018, no. 1, pp. 43-46.

18. Iarullin R.K., Valiullin R.A. et al. Optovolokonnye tekhnologii kontrolia tekhnicheskogo sostoianiia dobyvaiushchikh skvazhin [Fiber optic technologies for technical state control in producing wells]. *Karotazhnik*, 2014, no. 9 (243), pp. 47-55.

19. Naidanova E.S., Rybka V.F., Chudinov P.Iu. Dopolnitel'nye vozmozhnosti optovolokonnykh tekhnologii pri poiske negermetichnosti i goriachei promyvke skvazhiny [Extra capabilities of the fiber-optic technologies in leak-checks and hot-washing of the well]. *Karotazhnik*, 2018, no. 10 (292), pp. 39-47.

20. Samsonenko A.V., Samsonenko N.V., Simoniants S.L. Mekhanizmy vozniknoveniia i tekhnologii ustraneniia oslozhnenii protsessa tsementirovaniia obsadnykh kolonn [Mechanisms of occurrence and technologies for eliminating complications of the casing cementing process]. *Stroitel'stvo neftianykh i gazovykh skvazhin na sushe i na more*, 2016, no. 11, pp. 35-42.

21. Khrabrov V.A., Shut' K.F. Obzor i analiz matematicheskikh modelei snizheniia porovogo davleniia stolba tsementnogo rastvora v period OZTs [Review and analysis of mathematical models for decreasing the pore pressure of a cement slurry column in the waiting on cement (WOC) period]. *Stroitel'stvo neftianykh i gazovykh skvazhin na sushe i na more*, 2023, no. 1 (361), pp. 35-39. DOI: 10.33285/0130-3872-2023-1(361)-35-39

22. Kurbanov, Ia.M., Cheremisina N.A. Analiz tekhnicheskikh reshenii po predotvrashcheniiu postupleniia plastovykh fliuidov v zakolonnoe prostranstvo skvazhiny v period ozhidaniia zatverdevaniia tsementa [Analysis of technical solutions for preventing admission of formation fluids in the annular space of the well during the waiting on cement time]. *Izvestiia vysshikh uchebnykh zavedenii. Neft' i gaz*, 2019, no. 5 (137), pp. 64-71. DOI: 10.31660/0445-0108-2019-5-64-71

23. Shumilov A.V. Opyt ispol'zovaniia stantsii kontrolia tsementirovaniia na ploshchadiakh Permskogo Prikam'ia [Experience of using cementing control stations in the areas of the Perm Kama region]. *Tezisy dokladov nauchnogo simpoziuma "Novye tekhnologii v geofizike"*. Ufa: OAO NPF "Geofizika", 2001, pp. 86-87.

24. Koskov, V.N., Koskov B.V. Geofizicheskie issledovaniia skvazhin i interpretatsiia dannykh GIS [Geophysical surveys of wells and interpretation of well logging data]. Perm': Permskii gosudarstvennyi tekhnicheskii universitet, 2007, 317 p.

25. Tekhnicheskaia instruktsiia po provedeniiu geofizicheskikh issledovanii i rabot priborami na kabele v neftianykh i gazovykh skvazhinakh: RD 153-39.0-072-01. Vvedenie s 01.07.2001 [Technical instructions for conducting geophysical research and work with wireline instruments in oil and gas wells: RD 153-39.0-072-01. Introduction from 07/01/2001]. Moscow, 2001, 135 p.

26. Belov S.V., Shumilov A.V. Povyshenie dostovernosti opredeleniia kachestva tsementirovaniia obsazhennykh skvazhin po dannym akusticheskoi tsementometrii [Increasing the reliability of determining the quality of cementation of cased wells using acoustic cementometry data]. *Tezisy dokladov nauchnogo simpoziuma "Vysokie tekhnologii v promyslovoi geofizike"*. Ufa: OAO NPF "Geofizika", 2004, pp. 31-33.

27. Belov S.V., Shumilov A.V., Tashkinov I.V., Zaichkin E.V. Uchet vliianiia skvazhinnogo pribora pri akusticheskoi tsementometrii [Taking into account the influence of downhole tools during acoustic cementometry]. *Doklady III Rossiisko-Kitaiskogo simpoziuma "Novye tekhnologii v geologii i geofizike"*. Ufa: OAO NPF "Geofizika", 2004, pp. 90-96.

28. Belov S.V., Zaichkin E.V., Naugol'nykh O.V., Tashkinov I.V., Shilov A.A., Shumilov A.V. Sovershenstvovanie tekhnologii obrabotki dannykh GIS s pomoshch'iu novogo programmnogo kompleksa [Improving well logging data processing technology using a new software package]. *Tezisy dokladov nauchno-prakticheskoi konferentsii "Geofizicheskie issledovaniia skvazhin", posviashchennoi 100-letiiu promyslovoi geofiziki*. Moscow: Rossiiskii gosudarstvennyi universitet nefti i gaza imeni I.M Gubkina, 2006, pp. 65-66.

29. Tashkinov I.V., Shumilov A.V., Belov S.V., Zaichkin E.V., Naugol'nykh O.V., Shilov A.A. Sovershenstvovanie tekhnologii obrabotki dannykh GIS v programmnom komplekse "Sonata" [Improving well logging data processing technology in the "Sonata" software package]. *Doklady IV Kitaisko-Rossiiskogo simpoziuma "Noveishie dostizheniia v oblasti geofizicheskikh issledovanii skvazhin"*. Ufa: OAO NPF "Geofizika", 2006, pp. 206-215.

30. Guliaev P.N., Belov S.V., Naugol'nykh O.V., Shumilov A.V. Proizvodstvennyi opyt primeneniia kompleksa metodov AKTs i AKTs-S v OOO "PITTs "Geofizika" [Production experience in using a complex of ACC and ACC-S methods at LLC "PITC "Geophysics"]. *Tezisy dokladov nauchno-prakticheskoi konferentsii "Novye dostizheniia v tekhnike i tekhnologii GIS"*. Ufa: OAO NPF "Geofizika", 2009, pp. 74-76.

31. Kriuchatov D.N., Chukhlov A.S., Shumilov A.V. Skaniruiushchaia tsementometriia - effektivnyi sposob povysheniia informativnosti GIS v Zapadno-Sibirskom regione [Scanning cementometry is an effective way to increase the information content of well logging in the West Siberian region]. *Tezisy dokladov nauchno-prakticheskoi konferentsii "Novaia tekhnika i tekhnologii dlia geofizicheskikh issledovanii skvazhin"*. Ufa: NPF "Geofizika", 2010, pp. 162-164.

32. Pfister L., Lapo K., Mahrt L., Thomas Ch.K. Thermal submesoscale motions in the nocturnal stable boundary layer. Part 1: detection and mean statistics. *Boundary-Layer Meteorology*, 2021, vol. 180, no. 2, pp. 187-202. DOI: 10.1007/s10546-021-00619-z

33. Khalilov D.G. Volokonno-opticheskaia sistema aktivnoi termometrii [An optic fiber system for the active temperature measurements]. *Karotazhnik*, 2021, no. 3 (309), pp. 139-151.

34. Laptev A.P., Savich A.D., Kostitsyn V.I., Shumilov A.V., Sal'nikova O.L., Khalilov D.G. Primenenie optovolokonnykh sistem pri realizatsii kompleksnykh tekhnologii zakanchivaniia i dolgovremennogo monitoringa raboty skvazhin [The use of fiber-optic systems in the implementation of complex well completion technologies and long-term operation monitoring]. *Neftianoe khoziaistvo*, 2022, no. 8, pp. 94-99. DOI: 10.24887/0028-2448-2022-8-94-99

35. Filatov V.V., Bolotnova L.A. O tektonicheskom plane Verkhnekamskogo mestorozhdeniia kaliinykh solei po rezul'tatam fizicheskogo modelirovaniia i po geologo-geofizicheskim dannym [Upper Kama potassium salt deposit tectonic scheme based on physical modeling results and geological and geophysical data]. *Izvestiia vysshikh uchebnykh zavedenii. Gornyi zhurnal*, 2020, no. 5, pp. 38-46. DOI: 10.21440/0536-1028-2020-5-38-46

36. Ashikhmin S.G., Kukhtinskii A.E. Modelirovanie napriazhenno-deformirovannogo sostoianiia neobsazhennoi skvazhiny [Simulation of stress-deformed state of open well]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2014, vol. 13, no. 11, pp. 99-104.

37. Lebedeva O.O. Analiz i podgotovka iskhodnykh dannykh dlia postroeniia geologo-geomekhanicheskoi modeli uchastka Verkhnekamskogo mestorozhdeniia kaliino-magnievykh solei [Analysis and preparation of initial data for building a geological and geomechanical model of the area at the Verkhnekamskoye potassium-magnesium salt deposit]. *Nedropol'zovanie*, 2022, vol. 22, no. 3, pp. 139-143. DOI: 10.15593/2712-8008/2022.3.5

38. Shakirov A.A., Danilenko V.N. Sovremennoe sostoianie apparatury i metodiki ispytaniia plastov i otbora priborami na kabele [The current state of equipment and methods for testing formations and sampling with wireline instruments]. *Neft'. Gaz. Novatsii*, 2018, no. 2, pp. 46-49.

39. Tiurina G.V. Primenenie modul'nogo dinamicheskogo ispytatelia plastov na karotazhnom kabele dlia utochneniia fil'tratsionnykh kharakteristik produktivnykh plastov Magovskogo neftegazokondensatnogo mestorozhdeniia [Application of a Modular Dynamic Formation Tester on a Wire Line to Refine the Filtration Characteristics of the Production Formations of the Magovsky Oil and Gas Condensate Field]. *Nedropol'zovanie*, 2023, vol. 23, no. 1, pp. 25-31. DOI: 10.15593/2712-8008/2023.1.4

40. Diliavirov I.T., Abunagimov M.R., Isiangulov R.U., Mustafin A.M., Zmanovskii V.A., Luk'ianov N.N. Opyt ispol'zovaniia modul'nogo plastoispytatelia dlia resheniia razlichnykh geologicheskikh zadach [Experience of using the modular formation dynamics tester for solving different geological problems]. *Karotazhnik*, 2020, no. 2 (302), pp. 63-77.

41. Gabai H., Eyal A. On the sensitivity of distributed acoustic sensing. *Optics Letters*, 2016, vol. 41 (24), pp. 5648-5651. DOI: 10.1364/OL.41.005648

42. Daley T.M. et al. Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring. *The Leading Edge*, 2013, vol. 32 (6), pp. 593-724. DOI: 10.1190/TLE32060699.1

43. Dean T., Cuny T., Hartog A.H. The effect of gauge length on axially incident P-waves measured using fibre optic distributed vibration sensing: Gauge length effect on incident P-waves. *Geophysical Prospecting*, 2017, vol. 65 (1), pp. 184-193. DOI: 10.1111/1365-2478.12419

Библиографический список

1. Кислов, К.В. Распределенное акустическое зондирование: новый инструмент или новая парадигма / К.В. Кислов, В.В. Гравиров // Сейсмические приборы. – 2022. – Т. 58, № 2. – С. 5–38. DOI: 10.21455/si2022.2-1

2. Fibre Optic Monitoring of Groundwater Flow in a Drinking Water Extraction Well Field: Conference Proceedings, First EAGE Workshop on Fibre Optic Sensing. Amsterdam, 9-11 March 2020 / P. Kruiver, E. Obando-Hernández, M. Pefkos, M. Karaoulis, W. Bakx, P. Doornenbal, F. Ciocca, A. Chalari, M. Mondanos. – Amsterdam, 2020. DOI: 10.3997/2214-4609.202030010

3. Measurement, monitoring, verification and modelling at the Aquistore CO_2 storage site / Zeinab Movahedzadeh, Alireza Rangriz Shokri, Rick Chalaturnyk, Erik Nickel, Norm Sacuta // FIRST BRAKE. – 2021. – Vol. 39. – P. 69–75. DOI: 10.3997/1365-2397.fb2021013

4. Distributed electric field sensing using fibre optics in borehole environments / David L. Alumbaugh, Evan Schankee Um, G. Michael Hoversten, Kerry Key // Geophysical Prospecting. – 2022. – Vol. 70. – P. 210–221. DOI: 10.1111/1365-2478.13150

5. Peyman, Moradi. Fibre-optic sensing and microseismic monitoring evaluate and enhance hydraulic fracturing via real-time and post-treatment analysis / Peyman Moradi, Suresh Dande, Doug Angus // FIRST BRAKE. – 2020. – Vol. 38. – P. 65–72. DOI: 10.3997/1365-2397.fb2020067

6. Kuvshinov, B.N. Interaction of helically wound fibre-optic cables with plane seismic waves / B.N. Kuvshinov // Geophysical Prospecting. – 2016. – Vol. 64, no. 3. – P. 671–688. DOI: 10.1111/1365-2478.12303

7. Оценка возможностей применения технологии виброакустического воздействия (DAS) при мониторинге работы нефтяных и газовых скважин / И.Ю. Колычев, А.М. Денисов, С.В. Белов [и др.] // Проблемы разработки месторождений углеводородных и рудных полезных ископаемых. – 2022. – Т. 1. – С. 250–255.

8. Чугаев, А.В. Амплитудно-частотный отклик распределенного акустического сенсора DAS со спиральной намоткой волокна / А.В. Чугаев, М.В. Тарантин // Горные науки и технологии. – 2023. – Т. 8, № 1. – С. 13–21. DOI: 10.17073/2500-0632-2022-06-10

9. Чекалюк Э.Б. Термодинамика нефтяного пласта / Э.Б. Чекалюк. – М.: Недра, 1965.

10. Мониторинг температурного поля с помощью оптоволоконных технологий при площадных исследованиях / Е.С. Найданова, В.Ф. Рыбка, А.И. Губина, П.Ю. Чудинов // Каротажник. – 2020. – № 6 (306). – С. 82–91.

11. Distributed Temperature Sensing Monitoring of Well Completion Processes in a CO_2 Geological Storage Demonstration Site / D. Lee, K.G. Park, C.-N. Lee, S.-J. Choi // Sensors, Basel. – 2018. – Vol. 18. – P. 4239. DOI: 10.3390/s18124239

12. Lauber, T. Enhanced Temperature Measurement Performance: Fusing DTS and das Results / T. Lauber, G. Lees // IEEE Sensors Journal. – 2021. – Vol. 21, no 6. – P. 7948–7953. DOI: 10.1109/JSEN.2020.3046339

13. Найданова, Е.С. Опыт использования оптоволоконных технологий при геофизических исследованиях скважин / Е.С. Найданова, В.Ф. Рыбка, П.Ю. Чудинов // Каротажник. – 2019. – № 5 (299). – С. 62–72.
12. Ширяев, Е.О. Опыт применения оптоволоконных систем термометрии для исследования скважин / Е.О. Ширяев // Каротажник. – 2023. – № 6 (326). – С. 76–86.
15. Чудинов, П.Ю. Определение дебита скважин и учет добычи с использованием оптоволоконных технологий / П.Ю. Чудинов // Каротажник. – 2023. – № 6 (326). – С. 87–96.
16. Рыбка, В.Ф. Результат применения оптоволоконных технологий распределенной термометрии при освоении скважины с помощью ЭЦН / В.Ф. Рыбка // Экспозиция нефть газ. – 2013. – № 7 (32). – С. 13–16.
17. Рыбка, В.Ф. Волоконно-оптическая термометрия скважин. Мониторинг формирования газогидратной пробки /В.Ф. Рыбка, С.И. Васютинская // Научный журнал Российского газового общества. – 2018. – № 1. – С. 43–46.
18. Оптоволоконные технологии контроля технического состояния добывающих скважин / Р.К. Яруллин, Р.А. Валиуллин [и др.] // Каротажник. – 2014. – № 9 (243). – С. 47–55.
19. Найданова, Е.С. Дополнительные возможности оптоволоконных технологий при поиске негерметичности и горячей промывке скважины / Е.С. Найданова, В.Ф. Рыбка, П.Ю. Чудинов // Каротажник. – 2018. – № 10 (292). – С. 39–47.
20. Самсоненко, А.В. Механизмы возникновения и технологии устранения осложнений процесса цементирования обсадных колонн / А.В. Самсоненко, Н.В. Самсоненко, С.Л. Симонянц // Строительство нефтяных и газовых скважин на суше и на море. – 2016. – № 11. – С. 35–42.
21. Храбров, В.А. Обзор и анализ математических моделей снижения порового давления столба цементного раствора в период ОЗЦ / В.А. Храбров, К.Ф. Шуть // Строительство нефтяных и газовых скважин на суше и на море. – 2023. – № 1 (361). – С. 35–39. DOI: 10.33285/0130-3872-2023-1(361)-35-39
22. Курбанов, Я.М. Анализ технических решений по предотвращению поступления пластовых флюидов в заколонное пространство скважины в период ожидания затвердевания цемента / Я.М. Курбанов, Н.А. Черемисина // Известия высших учебных заведений. Нефть и газ. – 2019. – № 5 (137). – С. 64–71. DOI: 10.31660/0445-0108-2019-5-64-71
23. Шумилов, А.В. Опыт использования станций контроля цементирования на площадях Пермского Прикамья / А.В. Шумилов // Тезисы докладов научного симпозиума «Новые технологии в геофизике». – Уфа: Изд. ОАО НПФ «Геофизика». – 2001. – С. 86–87.
24. Косков, В.Н. Геофизические исследования скважин и интерпретация данных ГИС: учеб. пособие / В.Н. Косков, Б.В. Косков. – Пермь: ПГТУ, 2007. – 317 с.
25. Техническая инструкция по проведению геофизических исследований и работ приборами на кабеле в нефтяных и газовых скважинах: РД 153-39.0-072-01. Введ. с 01.07.2001. – М., 2001. – 135 с.
26. Белов, С.В. Повышение достоверности определения качества цементирования обсаженных скважин по данным акустической цементометрии / С.В. Белов, А.В. Шумилов // Тезисы докладов научного симпозиума «Высокие технологии в промысловой геофизике». – Уфа: Изд. ОАО НПФ «Геофизика», 2004. – С. 31–33.
27. Учет влияния скважинного прибора при акустической цементометрии / С.В. Белов, А.В. Шумилов, И.В. Ташкинов, Е.В. Заичкин // Доклады III Российско-Китайского симпозиума «Новые технологии в геологии и геофизике». – Уфа: Изд. ОАО НПФ «Геофизика», 2004. – С. 90–96.
28. Совершенствование технологии обработки данных ГИС с помощью нового программного комплекса / С.В. Белов, Е.В. Заичкин, О.В. Наугольных, И.В. Ташкинов, А.А. Шилов, А.В. Шумилов // Тезисы докладов научно-практической конференции «Геофизические исследования скважин», посвященной 100-летию промысловой геофизики. – М., Изд. РГУНГ им. И.М. Губкина, 2006. – С. 65–66.
29. Совершенствование технологии обработки данных ГИС в программном комплексе «Соната» / И.В. Ташкинов, А.В. Шумилов, С.В. Белов, Е.В. Заичкин, О.В. Наугольных, А.А. Шилов // Доклады IV Китайско-Российского симпозиума «Новейшие достижения в области геофизических исследований скважин». – Уфа: Изд. ОАО НПФ «Геофизика», 2006. – С. 206–215.
30. Производственный опыт применения комплекса методов АКЦ и АКЦ-С в ООО «ПИТЦ «Геофизика» / П.Н. Гуляев, С.В. Белов, О.В. Наугольных, А.В. Шумилов // Тезисы докладов научно-практической конференции «Новые достижения в технике и технологии ГИС». – Уфа: Изд. ОАО НПФ «Геофизика», 2009. – С. 74–76.
31. Крючатов, Д.Н. Сканирующая цементометрия – эффективный способ повышения информативности ГИС в Западно-Сибирском регионе / Д.Н. Крючатов, А.С. Чухлов, А.В. Шумилов // Тезисы докладов научно-практической конференции «Новая техника и технологии для геофизических исследований скважин». – Уфа: Изд. НПФ «Геофизика», 2010. – С. 162–164.
32. Thermal submesoscale motions in the nocturnal stable boundary layer. Part 1: detection and mean statistics / L. Pfister, K. Lapo, L. Mahrt, Ch.K. Thomas // Boundary-Layer Meteorology. – 2021. – Vol. 180, № 2. – P. 187–202. DOI: 10.1007/s10546-021-00619-z
33. Халилов, Д.Г. Волоконно-оптическая система активной термометрии / Д.Г. Халилов // Каротажник. – 2021. – № 3 (309). – С. 139–151.
34. Применение оптоволоконных систем при реализации комплексных технологий заканчивания и долговременного мониторинга работы скважин / А.П. Лаптев, А.Д. Савич, В.И. Костицын, А.В. Шумилов, О.Л. Сальникова, Д.Г. Халилов // Нефтяное хозяйство. – 2022. – № 8. – С. 94–99. DOI: 10.24887/0028-2448-2022-8-94-99
35. Филатов, В.В. О тектоническом плане Верхнекамского месторождения калийных солей по результатам физического моделирования и по геолого-геофизическим данным / В.В. Филатов, Л.А. Болотнова // Известия высших учебных заведений. Горный журнал. – 2020. – № 5. – С. 38–46. DOI: 10.21440/0536-1028-2020-5-38-46
36. Моделирование напряженно-деформированного состояния необсаженной скважины / С.Г. Ашихмин, А.Э. Кухтинский // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2014. – Т. 13, № 11. – С. 99–104.
37. Лебедева, О.О. Анализ и подготовка исходных данных для построения геолого-геомеханической модели участка Верхнекамского месторождения калийно-магниевых солей / О.О. Лебедева // Недропользование. – 2022. – Т. 22, № 3. – С. 139–143. DOI: 10.15593/2712-8008/2022.3.5
38. Шакиров, А.А. Современное состояние аппаратуры и методики испытания пластов и отбора приборами на кабеле / А.А. Шакиров, В.Н. Даниленко // Нефть. Газ. Новации. – 2018. – № 2. – С. 46–49.
39. Тюрина, Г.В. Применение модульного динамического испытателя пластов на каротажном кабеле для уточнения фильтрационных характеристик продуктивных пластов Маговского нефтегазоконденсатного месторождения / Г.В. Тюрина // Недропользование. – 2023. – Т. 23, № 1. – С. 25–31. DOI: 10.15593/2712-8008/2023.1.4
40. Опыт использования модульного пластоиспытателя для решения различных геологических задач / И.Т. Дилявиров, М.Р. Абунагимов, Р.У. Исянгулов, А.М. Мустафин, В.А. Змановский, Н.Н. Лукьянов // Каротажник. – 2020. – № 2 (302). – С. 63–77.
41. Gabai, H. On the sensitivity of distributed acoustic sensing / H. Gabai, A. Eyal // Optics Letters. – 2016. – Vol. 41 (24). – P. 5648–5651. DOI: 10.1364/OL.41.005648
42. Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring / T.M. Daley [et al.] // The Leading Edge. – 2013. – Vol. 32(6). – P. 593–724. DOI: 10.1190/TLE32060699.1
43. Dean, T. The effect of gauge length on axially incident P-waves measured using fibre optic distributed vibration sensing: Gauge length effect on incident P-waves / T. Dean, T. Cuny, A.H. Hartog // Geophysical Prospecting. – 2017. – Vol. 65(1). – P. 184–193. DOI: 10.1111/1365-2478.12419

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