High-resolution pressure transducer design and associated circuitry to build a network-ready smart sensor for distributed measurement in oil and gas production wells

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Abstract
Miniaturized single-mode thickness-shear pressure transducer combined with high-temperature SOI, silicon on insulator, integrated circuit technology is proposed as network-ready high-pressure high-resolution smart sensor for distributed data acquisition in oil and gas production wells. The transducer miniaturization is investigated with a full 3D computer model previously developed by the authors to assess the impact of intrinsic losses and various geometrical features on transducer performance. Over the last decades there has been a trend toward size reduction of high-resolution pressure transducer. The implemented model provides insight into the evolution of high-resolution pressure transducers from Hewlett-Packard™ to Quartzdyne™ and beyond. Distributed measurement in production oil wells in extreme harsh environment, such as found in the pre-salt layer, is an unsolved problem. The industry move toward electrified wells offers an opportunity for application of smart sensor technology and power line communications to achieve distributed high-resolution data acquisition.

Keywords Piezoelectric transducer · Quartz resonator · High-T SOI · Graphene electrode · Pressure · Temperature · Power line communications · Smart sensor · Oil and gas well

Introduction
High-resolution pressure and temperature measurements are key data for reservoir assessment or well management. They are used in drill stem test, DST, or wireline formation test, WFT, to estimate reservoir permeability, fluids present, flow rate and oil/water interface for optimal well completion. In the production phase, analysis of collected data can be used in well planning for economically optimal and safe production.

Assuming there is no drift and no operator or calibration errors, the main sources for measured data variation are intrinsic and environment noise, including wellbore pressure fluctuations (Ennaifer and Kuchuk 2018). For the downhole pressure sensor is desirable to be capable of detecting fluctuations under 20 Pa for early pressure buildup detection which is used to monitor well performance and stability during drilling, reservoir assessment and production phases (Sinha and Patel 2016; Zhang 2019). For pressure and temperature profile acquisition along the wellbore this

\[
\frac{100\text{Pa}}{100\text{MPa}} = \frac{1}{10^6} = 1 \text{ ppm}.
\]

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specification could be sacrificed to achieve enough size reduction which could allow for distributed data acquisition. Roughly speaking, resonator-type transducer resolution is related to the inverse of the transducer quality factor, Q-factor. Thus, transducer Q-factor greater than one million is set as a figure of merit Sinha and Patel (2016); Zhang (2019); Matsumoto et al. (2000). The standard transducer technology to achieve such high Q-factor is the piezoelectric resonator-type transducer made of quartz, as it displays excellent sensitivity, frequency stability with respect to cut error, long-term stability, pressure and temperature cycling stability, and rugged characteristics Matsumoto et al. (2000); Besson et al. (1993); Patel and Sinha (2018); Watanabe and Watanabe (2002); Vig and Walls (2000); Sinha (2001); Spassov et al. (2008); Ward and Wiggins (1997). In some high-temperature applications gallium phosphate, GaPO₄, may be a material of choice as its phase transition temperature is at 97 °C Krempl et al. (1997). Other candidates are langasite Sinha and Patel (2016); Smythe (1998) and tourmaline which displays no phase transition up to its decomposition temperature Handerson (1971).

The first high-resolution pressure transducer used in the oil and gas industry was the disk plate combined with two caps, shown in Fig. 1, developed by Hewlett-Packard™ in the 1960’s. Since this early transducer there has been an evolution in terms of size reduction and vibration mode utilized. Smaller transducer dimension helps reducing costs while improving thermal transient response and alleviating possible dead-volume calibration problems. One should keep in mind that less volume reduces power handling capability and absolute accuracy. Nowadays, two different transducer geometries are commonly used: Schlumberger™ and Quartzdyne™ (now ChampionX™). The Quartzdyne transducer displays the same geometry shown in Fig. 1. To complete the pressure sensor, besides the crystal transducer, one has to provide conditioning, processing and communications electronics board sealed in a stainless steel packaging. However, electronic circuit module dimensions, lack of electrical power supply in the wellbore, transducer dimensions, and costs have limited sensor deployment to single point measurement. It is mounted in a structure at the welltop, named X-mas tree, or at the well bottom in which is deployed as the Permanen Downhole Gage, PDG Silva Junior et al. (2012); Silva and Santos (2019); Silva and Santos (2012, 2013); Silva (2014). For the Quartzdyne™ the finished sensor length is over 500mm. Maximum pressure and resolution of commercial pressure transducers are presented in Table 1.

Fiber optics based sensor is a competing technology which has been used successfully for permanent or temporary distributed measurements Feo et al. (2020); Lumens (2014); Bao and Chen (2012). In harsh environment in deep underwater wells in the pre-salt layer, under high pressure and high temperature, contaminant gases, such as sulfide gas, can diffuse into and darken the fiber resulting in reliability problems or measurement failure Marriott et al. (2016); Reshetenko et al. (2002).

The goal of this investigation is to develop a pressure and temperature smart sensor which can be deployed along a wellbore to measure pressure and temperature profiles. Thus, transducer geometry miniaturization, high temperature electronics, packaging, water tight connector, and communications wiring and protocol must be addressed. Firstly, the miniaturization limit is investigated with the full 3D computer model previously developed and validated by the authors to assess the impact of intrinsic losses and various geometrical features on transducer performance Silva and Santos (2019). The Hewlett-Packard type transducer geometry is selected as prototype to investigate the smallest dimension while keeping the Q-factor over 10⁶. Based on the obtained results a miniaturized thickness-shear 3D transducer combined with high-temperature silicon on insulator, SOI, integrated circuit technology is proposed as a network-ready high-pressure high-resolution smart sensor. This sensor technology has the potential of provoking a paradigm shift in pressure measurement in oil and gas well as it allows for distributed data acquisition. The paper is divided into four sections, this introduction is first. Next, the previously developed 3D-FEM (Finite Element Method) computer model is applied to investigate the smallest pressure transducer geometry with at least 10⁶ Q-factor. In the third section is discussed how the obtained transducer can be combined with high-T SOI technology to build a network-ready high-pressure high-resolution smart sensor able to communicate over the power line. Finally the conclusion.

### Table 1 Maximum pressure and resolution of commercial pressure transducers

| Manufacturer        | Maximum pressure (MPa) | Resolution (Pa) |
|---------------------|------------------------|-----------------|
| Hewlett-Packard™    | 80                     | 70              |
| Quartzronic™        | 110                    | 70              |
| Schlumberger™       | 103                    | 20              |
| Quartzdyne™         | 110                    | 41              |
Pressure transducer

High-resolution pressure sensor used in oil production well was first developed by Hewlett-Packard™ in the 1960’s, and was released to the market in the early 1970’s. Only in 1988, Quartztronic™ (Halliburton™) released a smaller and improved version of the Hewlett-Packard transducer. Four years later, Quartzdyne™ (now ChampionX™) and Schlumberger™ released new different transducers with further size reduction. To get an insight into this evolution process and to better understand the impact of transducer geometry and dimensions on Q-factor, a full 3D computer model was developed and validated by the authors Silva and Santos (2019). In the model validation process the simulated transducer was compared to commercially available transducer of equal geometry and dimension Silva and Santos (2014); Silva and Santos (2019); Silva and Santos (2012, 2013); Silva (2014). In the developed computer model intrinsic energy loss is taken into account as a viscosity parameter. Thus, the Q-factor is inversely proportional to the viscosity, \( \eta \), of the piezoelectric material. For thickness-shear mode resonator-type quartz transducer with the AT-cut,

\[
Q = \frac{c_{66}}{\omega \eta_{66}},
\]

in which \( c_{66} = c_{66}(1 + k_{26}^2) \) is the constant of piezoelectric coupling, \( c_{66} = 29.01 \times 10^9 \text{ N/m}^2 \), \( k_{26} = \frac{c_{26}}{c_{66}} \approx 0.0078 \), \( \eta_{66} = 3.2 \times 10^{-4} \text{ Pa} \).

Using the developed model simulations were carried out with the Hewlett-Packard type design with dimensions larger and smaller than the current Quartzdyne™ transducers to investigate the size limit while keeping Q-factor above \( 10^6 \). Both, Quartz and GaPO\(_4\) transducers were analyzed. The simulation results for the Q-factor as a function of frequency for diameters ranging from 90 mm down to 5 mm are presented in Fig. 2. In this simulation the transducer surfaces are flat, known as plano-plano geometry, and vibrates in the thickness-shear mode, with a frequency inversely proportional to the plate thickness, \( t \),

\[
f_n = \frac{n}{2t} \sqrt{\frac{c_{66}}{\rho}},
\]

in which \( \rho = 2649 \text{ kg/m}^3 \) for AT-cut quartz.

Based on the results presented in Fig. 2 to achieve \( 10^6 \) Q-factor in the plano-plano geometry the transducer diameter must be 30 mm or larger. Notice that this is approximately the diameter of the first transducer introduced by Hewlett-Packard \( (d_{\text{HP}} = 25.4 \text{ mm}) \) which is a good validation of the implemented model. Furthermore, it is interesting to notice that the 5-mm diameter transducer should be capable of achieving over \( 10^7 \) Q-factor which is a good surprise.

Contact electrode thickness causes loading which further reduces the Q-factor. However, there is a trade-off between electrode thickness and electrode coverage. Still considering the plano-plano geometry the impact of electrode coverage on the Q-factor was analyzed and the results are summarized in Fig. 3 in which \( d_e \) is the electrode diameter and \( d \) is the transducer diameter for the plano-plano geometry for \( f = 8.32 \text{ MHz} \) \( (t = 200 \mu\text{m} \text{ is the transducer thickness}) \).
To achieve higher Q-factor at smaller diameters one has to abandon the plano-plano geometry. The strategy to reduce losses is to concentrate the energy within the plate transducer under the contact layer which can be achieved by modifying the plate surface topology. The plano-convex is the selected geometry and a new set of simulations is carried out for 6 mm plate diameter down to 3 mm. The results are presented in Fig. 4. From the simulations it is observed that for the 5-mm diameter transducer the Q-factor can get over $10^6$ should a curved surface be realized with curvature height at the disk plate center, $h_c$, of 60 μm. Such transducers can be manufactured with ultrasound machining. For smaller dimensions MicroElectroMechanical System, MEMS, manufacturing techniques used for microlens fabrication can be applied Roulet et al. (2001); Liu et al. (2019); Yuan et al. (2018); Lin and Wen (2021).

The transducer with caps response to pressure and temperature for $d = 5$ mm and $d = 30$ mm is shown in Fig. 5. For comparison, at 25 °C the pressure sensitivity, $S_p$, of the 30-mm plate is approximately 432 Hz/MPa and the sensitivity of the 5-mm plate is approximately 200 Hz/MPa. For the Quartzdyne transducer ($d_{QD} = 14.7$ mm) the sensitivity is 363 Hz/MPa which is another validation of the model. The model was implemented in COMSOL Multiphysics Software (COMSOL multiphysics FEM software v. 4.4 2014).

The transducer specifications are summarized in Table 2, patent pending Santos and Silva (2017). The proposed transducer has a diameter, $d$, of 5 mm with a curved (convex) surface at one side whose height at the center point is $h_c = 60$ μm, with two caps, as shown in Fig. 1. It can be mounted in a 3/8-inch stainless steel tube, e.g, 316L, incoloy 705, 718, 825 or AISI 4140. For comparison the Hewlett-Packard transducer diameter is 25.4 mm and can measure up to 80 MPa with 70 Pa resolution, and the Quartzdyne transducer diameter is 14.7 mm and can measure up to 110 MPa with 41 Pa resolution. The Hewlett-Packard transducer is 86.4 mm long, while the Quartzdyne is 15.2 mm long. The pressure transducer evolution is shown in Fig. 6 and compared to the transducer proposed in this paper Silva and Santos (2013); Silva (2014).
In commercial high-resolution pressure sensor for the oil and gas industry, such as the Quartzdyne™ transducer, ceramic-based electronic circuitry is used to achieve high temperature operation. Commercially available sensors are not suitable for distributed measurement due to its large size. For the Quartzdyne™ the finished sensor length is over 500 mm.

For the proposed sensor, to achieve high-temperature operation at smaller dimensions, high-T SOI technology is selected Santos and Vasconcelos (2014). For example, the HO35 mixed signal process from Fraunhofer IMS displays channel length of 360 nm for digital blocks and 1.0 μm for analog blocks. Circuits are operational up to 300 °C Kappert et al. (2015, 2014); Vanhoenacker-Janvier et al. (2008). This is enough to integrate the needed functions to build a smart sensor node. To make a compact sensor with reduced parasitics, the sensing oscillator chip could be placed on top of one of the caps, as shown in Fig. 7. A second crystal transducer attached to an RF oscillator is used for temperature measurement. Another possible technology for temperature measurement is the resistance temperature detector, RTD Santos and Vasconcelos (2008).

**Smart sensor**

A smart sensor is a combination of transducer, conditioning electronics, signal processing and data communication, as described in IEEE 1451.2 standard (IEEE Standard for Smart Transducer 1997). Transducer and electronics should all be included in a single packaging. Furthermore, it can all be integrated into a single chip as the ultimate goal of MEMS technology. A smart sensor is capable of plug-and-play operation, self-diagnose, linearity correction, increased signal-to-noise ratio. The proposed smart sensor node block diagram designed for power line communications is presented in Fig. 8. It can run a lightweight real-time monitor or light operating system, such as TinyOS (TinyOS 2012) with real-time extension. An operating system is preferable as it offers more flexibility. Local memory can be used for temporary data storage, data formatting and for Transducer Electronic DataSheet, TEDS, information. One particular challenge has to be addressed, namely: the sensor connector. This is a multisensor deployment, and the connector should provide water tight connection to the sensor node itself and two neighboring sensor nodes. However connector technology already in use for PDG deployment is a starting point.

**Frequency to digital converter**

For the thickness-shear transducer discussed in Section 2 a conditioning circuitry is required to extract the measured physical quantity. As the transducer behaves as a large low-loss inductor between series and parallel frequencies Sobral and Santos (2013) the Pierce oscillator topology can be used

| Parameter                  | Value                      |
|----------------------------|----------------------------|
| Material                   | Quartz                     |
| Cut                        | AT                         |
| Plate diameter, $d$ (mm)   | 5                          |
| Plate thickness, $t$ (μm)  | 200                        |
| Plano-convex, $h_c$ (μm)   | 60                         |
| Diameter with caps, $d$ (mm) | 6.5                     |
| Transducer length, $l$ (mm)| 9.5                       |
| Maximum pressure, $p$ (MPa)| 137.89                    |
| Resolution (ppm)            | < 10                       |
| Sensitivity, $S_p = \Delta f/\Delta p$ (Hz/MPa) | 191.04 (@ 25 °C) | 220.91 (@ 200 °C) |

**Table 2** Transducer specifications for distributed pressure profile measurement
as sensing oscillator in which the crystal is replaced with the transducer as shown in Fig. 9. The frequency changes with the detected physical quantity variation. Thus, the oscillator acts as a physical quantity to frequency converter. The oscillator can be designed such as the free running frequency, \( f_0 \), is the first or the third harmonic of the transducer vibration mode. The Quartzdyne sensor runs at \( f_0 = 7.2 \) MHz. According to Eq. 3 for the sensor specified in Table 2, \( f_o = f_1 = 8.30 \) MHz.

The acquisition method is frequency counting [43]. In the simplest scheme a fixed gate time period, \( T_G \), is set and the amount of up or down transitions of the sensing oscillator is registered with a counter. The gate time period is a function of a fixed number of up or down transitions, \( N_R \), of the reference oscillator, \( T_G = N_R/f_R \). Thus pressure resolution is a function of gate time period, \( T_G \), and pressure sensitivity, \( S_p \),

\[
R_p = \frac{1}{T_G \times S_p}. \tag{5}
\]

Long gate time period is required to achieve high resolution which is a disadvantage of this technique.

Next strategy is named reciprocal counting. In this scheme the sensing oscillator is counted for a fixed number of up or down transitions, \( N_S \), while the reference oscillator is accumulated [43]. Should the reference oscillator frequency be larger than the sensor oscillator frequency resolution is improved.

\[
R_p = \frac{f_S^2}{f_R \times N_S \times S_p}. \tag{6}
\]

To make the sensing frequency much smaller than the reference frequency a mixer is introduced. The sensing frequency is downshifted by mixing with the reference oscillator signal to generate a low frequency signal representing the frequency deviation, \( \Delta f_S \). This low frequency signal is fed to the frequency to digital converter. The resolution is now,

\[
R_p = \frac{(\Delta f_S)^2}{f_R \times N_S \times S_p}. \tag{7}
\]

Based on Fig. 5 for \( \Delta f_S \approx 20\text{kHz} \) and 16-bit counter,

\[
R_p = \frac{(20 \times 10^3)^2}{8.3 \times 2^{16} \times 200} = 3.7 \text{ Pa.} \tag{8}
\]

Acquisition time is,

\[
T_{acq} = \frac{2^{16}}{20 \times 10^3} = 3.3 \text{ s.} \tag{9}
\]

For pressure profile in oil well there is no need to use very high resolution which allows for faster acquisition rates. For 12-bit counter acquisition time is 0.2s and pressure resolution is \( R_p = 58.8\) Pa. A high-resolution frequency-to-digital converter was developed by the authors in VHDL (Hardware Description Language) and synthesized in FPGA (Field Programmable Gate Array). It was tested up to 10MHz and up to 30-bit wide counter. It is capable of 1 ppm resolution Silva and Santos (2010). It was later manufactured as ASIC (Application Specific Integrated Circuit) in the 0.35\( \mu \)m technology at AMS foundry through Europractice, as shown in Fig. 10 Silva and Santos (2010).

The raw data from the frequency to digital converter is fed to the digital processor which formats the data package for the power line communications module. Oil and gas flow is a slow process compared to electronic circuit timing, thus data acquisition module with the high-resolution frequency-to-digital converter runs independently and only requires the digital processor attention as the conversion ends.

**Implementation** The prototype sensor node digital circuitry and Pierce oscillator was constructed as a multiboard circuit using FPGA for benchtop evaluation. For the ASIC...
approach the estimated chip area of the complete design is shown in Table 3.

**Smart sensor network**

The sensor network for oil and gas well must be robust, incorporate redundancy to be fault tolerant, fault-safe operation, self-diagnose. It is expected to achieve real-time operation, thus it is required to have known latency, cyclic data transmission and isochronous operation. Differently from typical industrial applications, sensor robustness and reliability is far more critical and has to be combined with sensor compactness for distributed measurement. Like a space mission the network must be deployed to last 10 years or more.

The proposed smart sensor, shown in Fig. 8, must transmit collected data to a control room to generate the desired profile. As the oil and gas industry moves toward electrified wells, the sensor node does not need to harvest energy or use a non-standard energy source, such as thermonuclear battery. Besides, electrical energy being supplied inside the well opens the possibility for communication over the power line, eliminating the need for dedicated network wiring to achieve distributed high-resolution measurement.

**Cable technology** In oil wells there is a cable technology already in usage for pressure measurement data transmission, such as the PDG cable from Schlumberger, shown in Fig. 11. The cable is uniform, there is no variable cross-sectional wiring or different conductor types. According to the Schlumberger datasheet, cable DC resistance is 23 Ω/km at 20 °C, 36 Ω/km at 150 °C, and capacitance is 100 pF/m (2014).

To evaluate cable response to high frequency signal, two SMA connectors were attached to an one-meter long cable sample and the transmission and reflection measurements were carried out with the HP8714 vector network analyzer. A plot is presented in Fig. 12. At 15 MHz cable transmission loss is 0.3 dB. The measured cable DC resistance is under 0.1 Ω/m. As the transmission frequency increases, signal propagation moves toward the wire surface and the effective AC resistance is larger.

Based on the measured scattering parameters, the cable impedance is estimated to be approximately 60 Ω, and its transfer function is linear. Thus, the cable is capable of high-rate data communications. This cable technology is suitable for data transmission and to supply energy to the proposed smart sensor network. There is still the challenge of adapting the already existent connector technology for correct electrical impedance and reliable sensor attachment along a single cable.

**Network communications** Power line communications, PLC, is a technology under development for over a century. It uses Quadrature Amplitude Modulation, QAM, combined with Orthogonal Frequency Domain Multiplexing, OFDM, for reliable data transmission in noisy environment. Nowadays, there are a multitude of technologies, such as: HomePlug™, ISO/IEC 14908, ITU T G.hn and IEEE1901 HomePlug AV specification (2014); Power line channel specifications (2012); International Telecommunication

Table 3 Floorplan area estimation for a 5×5 mm² chip in the 360 nm technology node

| Circuit block                  | Area (mm²) |
|--------------------------------|------------|
| Pierce oscillator (×3)         | 1.5        |
| Frequency to digital converter (×2) | 2.0       |
| Mixer + filter (×2)            | 2.0        |
| ROM/RAM                       | 8.0        |
| Processor                     | 4.0        |
| Communications (IFFT/FFT)      | 7.5        |
| TOTAL                         | 25.0       |

![Fig. 11 Coaxial cable used for PDG data communication in oil well. On the right is an image of the electrical cable combined with stainless steel cables on each side for mechanical strength](image-url)
Network topology and protocol  The network topology is centralized with a coordinator master node, but due to the depth of the well the coordinator node cannot be reached by most sensor nodes. One criteria to improve fault tolerance is to establish that each node should be capable of contacting at least three neighbors upstream and another three neighbors downstream. To avoid the single point of failure problem, a second or third coordinator node can be used as slave coordinators. The redundant coordinator nodes listen to all messages and records all replies, as if it were the real coordinator. It only does not initiate a conversation. It looks like a long queue or stretched mesh topology. For this smart sensor network the bucket-brigade inspired network protocol is proposed Santos (2021).

**Metrological factors**

Assuming there is no drift and no operator or calibration errors, the main sources for measured data variation are intrinsic and environment noise, including wellbore pressure fluctuation Ennaifer and Kuchuk (2018). The circuitry must include intrinsic and environment noise, including wellbore pressure fluctuations, environment noise and transducer loss to achieve permanent oscillation. The loop circuit is tuned to oscillate close to the transducer series resonance, thus the loop impedance

\[ Z_{\text{loop}} = \frac{1}{j\omega C_t} \approx j2QR_m \frac{\Delta \omega}{\omega} \]

in which \( C_t = C_m \parallel C_a \) and \( C_a \) is the amplifier equivalent capacitance.

Such noise sources translate into oscillator phase noise which causes a random fluctuation of the oscillator frequency Santos (2021); Vittoz (2010). The noise to signal power ratio is,

\[ \mathcal{L} = \frac{S_{\text{in}} + S_{\text{ov}}}{|Z_{\text{loop}}|^2} \frac{2}{2(1 + \gamma)k_B T} \frac{2}{P_{\text{signal}}} \]

For the transducer proposed in Sect. 2, \( f_o = f_m = 8.3\text{MHz}, \) \( Q = 10^6, T = 500\text{K} \) and oscillator with \( \gamma = 2, P_{\text{signal}} = 0.1 \text{mW} \). For \( \Delta f = 1\text{Hz} \),

\[ \mathcal{L}_{\text{dBc}} = -141.5 - 20\log \Delta f = -141.5 \text{ dBc} \]

Thus, the intrinsic noise contribution to measurement fluctuation is negligible. The main source of fluctuation in the proposed transducer is from the environment. One can apply appropriate statistical techniques to extract the desirable measurement Ennaifer and Kuchuk (2018).

**Conclusion**

Based on simulation results obtained with the validated full 3D FEM computer model developed by the authors one can conclude there is still room for further miniaturization. The 5-mm or larger transducer can be designed to achieve over \( 10^6 \) Q-factor in the plano-convex geometry. The proposed quartz transducer is capable of withstanding pressures greater than \( 137.89\text{MPa} \) at temperatures up to \( 200 \degree \text{C} \) with less than 20\%Pa resolution depending on frequency to digital counter resolution. The 3D-FEM computer model developed by the authors has provided insight into the evolution process of high resolution transducers used in the oil and gas industry since the 1970’s. It was validated for the disk-shaped AT-cut quartz transducer as a function of the hydrostatic pressure and compared to commercially available transducers.

The miniaturized transducer geometry combined with high-T SOI technology allows for the manufacturing of high-resolution pressure smart sensor for oil and gas well pressure profile acquisition. If needed the proposed distributed measurement network can be combined with a single point PDG meter for redundancy and for extra resolution in detecting early pressure build up. The smart sensors can carry out data transfer with the bucket-brigade protocol. One particular challenge must be addressed, namely: the sensor connector. This is a multisensor deployment and the connector should provide water tight connection and allow for connection of two neighboring sensor nodes with mechanical strength. The proposed smart sensor...
technology has the potential of provoking a paradigm shift in pressure measurement in oil and gas well.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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