ENERGY HARVESTING IN HORIZONTAL DRILLING PROCESSES FOR THE PURPOSE OF INFORMATION AND NAVIGATION MONITORING

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Abstract: *Precise information and navigation monitoring in horizontal drilling is of great importance for oil exploration and deposit discovery. The cost of the drilling process depends significantly on drilling precision. The necessary drilling accuracy is provided by navigation and information-gathering instruments which need electrical power in order to operate. Small available volume, long drilling times, vibrations, and high temperatures are typical constraints for any power supply source used in downhole drilling. Downhole navigation and information-gathering systems become increasingly complex, with more strict demands for the parameters of their electrical power supply.*

Batteries and conventional power cables are the traditional and the most utilized power supply sources downhole. Both have significant disadvantages and increase the cost of drilling operations. Short lifespan of the batteries and high susceptibility to failure of the cables in the harsh downhole environment are the main motivators for further research in self-sustaining energy sources. Ideally, downhole navigation instruments and information-gathering sensors (e.g. pressure, temperature, etc.) need autonomous power supply with electrical energy produced in situ. This would improve significantly the efficacy of the entire drilling process.

This article presents a review of the existing and the emerging concepts related to utilizing the available energy sources in downhole drilling. The advantages and the drawbacks of these energy-harvesting concepts are discussed and compared to conventional power sources. Progress in the development of some of these concepts is illustrated by industrial examples. Some fairly new approaches to electrical energy supply for the information exchange downhole are also presented in order to inspire non-traditional research in this field.

Keywords: *Energy harvesting, Horizontal drilling processes, Oilfield Instrumentation, Measurement-While-Drilling.*

ACM Classification Keywords: *A.0 General Literature - Conference proceedings; J.2 Physical Sciences and Engineering*

Introduction

A. Downhole electronics and instrumentation

There are three main areas of applications of downhole information-processing electronics: Wireline Data Logging (WDL), Measurement-While-Drilling (MWD)/Logging-While-Drilling (LWD), and Intelligent Completions [1, 2].

The first area of applications delivers captured data based on gamma rays, seismic waves, electromagnetic waves, acoustic waves or vibrations. The electronics for this application area is commonly connected to subsurface and surface-based recording points [3].

The second area comprises devices directly mounted behind the drill bit [2]. They can detect the drill bit position in space or measure physical, mineral or organic material characteristics within the well. These are typically battery-run measurements. Harsh downhole conditions such as high temperatures, shocks and severe vibrations are critical factors disturbing reliable operations.

The third area of downhole applicability includes sensors that measure long-term such parameters as oil and gas pressure within the well in stationary conditions [3]. These devices enable management of data that relate to the quality and the productivity of the well. Installations take place within the well and provide key analytical data throughout the entire lifetime of the well, not during drilling.

The information obtained from downhole electronics is vital for improving drilling precision, well management, and cost efficiency.

B. Traditional energy supplies downhole

Electrical power for supplying downhole instrumentation is usually provided by batteries directly mounted downhole. It can also be transmitted from the surface via conductors, such as cables or wirelines [4].

Downhole batteries have the capability of storing a finite amount of power and have temperature limitations. According to industrial specifications [5], a typical cell unit delivers from 3 V to 4 V in open-circuit conditions. Power demands in the range of 30 - 120 W can be met by a battery pack of several cells connected in series. The main drawback of battery utilization downhole is the fact that the batteries' chemistry necessitates periodic replacement. Rechargeable batteries capable of operating at very high temperatures are still not available [5], and special measures need to be taken to protect them from temperatures higher than 170º C. Temperatures downhole of a well can reach 200º C during drilling [5].

The alternative to downhole batteries is conventional power cabling [4]. This approach to power-supplying downhole instrumentation does not have energy-delivery limitations [6]. However, the cables are carried to their deployment point by being attached to the exterior of the drilling pipe. Thus, they are subjected to severe friction, shear forces and very high temperatures and pressures. Therefore, the cables are highly susceptible to failure. Additionally, they are limited in length because at long distances they might break under their own weight. On the other hand, cables require special deployment techniques which in the constrained space downhole obstruct the production mud flowpath. This prevents the use of safety equipment and limits the flow rate of the mud which is essential for facilitating the drilling process.

Despite that both approaches enable supply of enough electrical energy downhole, they have their limitations and are considered too costly [6].

C. Downhole instrumentation power demands

This article is focused on the issue of supplying the main energy consumers downhole during the drilling process itself, the MWD/LWD instruments for information-gathering and navigation. The amount of electric power used by these consumers ranges between 600 and 900 W [7]. A portion of this power (80 to 200 W) is utilized for data collection by sensors, of which for navigation purposes only a range of 40 – 60 W is needed. The rest is utilized for data transmission to the surface.

D. Aim of the paper

This article reviews different concepts for supplying electrical energy downhole and discusses their feasibility. Many of the discussed approaches are already employed in the present-day drilling processes with variable efficiency, others are only suggested, and some have never been applied downhole.

Despite the fact that batteries are more broadly utilized as power sources downhole, other power supplying devices are emerging or are under development. Any new approach introduces the possibility of employing new and previously unnoticed energy sources available during the drilling process, an approach known as energy harvesting. Such systems aim at creating autonomous power supplies for the downhole navigation and information-gathering instrumentation. The objective of this study is to review the existing means of power supplying and to discuss the pre-conditions for emerging novel approaches to energy harvesting downhole.

Review of energy sources downhole

Drilling conditions downhole, and particularly the dynamic drilling process, provide different types of energy, ranging from mechanical to thermal. In order to utilize this available energy, it should be transformed into electricity. There are patented devices transforming different types of energy present during downhole drilling processes, including kinetic [8 - 10], vibrational [6, 11 - 14], thermal [7], electrostatic [15], and chemical [16] energy. These energy sources necessitate the use of associated energy-converting devices that transform the harvested energy into electricity.

Analysis and practical feasibility evaluation of all energy-transforming concepts are given below (Table 1).

Table 1. Comparison between different power sources downhole

Energy Source	Maximum Estimated Power Per Single Unit [W]	Transforming Means	Achieved Generated Power [W]	Industrial Applicability [Yes/No]	Source/ Patent
Battery	20	Direct	120	Y	[5]
Kinetic	800	Turbine/ Eccentric	15	Y	[8 - 10]
Vibration	1200	Electromagnetic coil/ piezo-element	30	Y	[6, 11 - 14]
Thermal	0.01	Thermocouple	No data	N	[7]
Electrostatic	10	Capacitor	No data	N	[15]
Chemical	2000	Fuel cell	1000	Y	[5,16]

A. Kinetic energy sources

The production mud fluid utilized in the drilling process is one of the main sources of kinetic energy. The passing mass of mud fluid, with a speed reaching 100 liters-per-second, delivers mechanical power in the range of hundreds of Watts. The main means of converting this power into electricity is by utilizing a turbine [8, 9]. According to one patent [8], the rotor of an electrical generator receives its motion from a rotating external turbine coupled to it. The turbine is rotated by the kinetic force created by the mud that flows in the fluid passageway of the string tubing. The problem with this approach is that the turbine is axially-placed in the tubing, which decreases the effective diameter of the latter. Thus, the mud flow rate decreases. There are proposals for placing the turbine laterally [9]. The housing includes a laterally displaced side passageway, so that the production mud fluid passes with less friction through the tubing. The generator is located at least partially in or along the side passageway [9]. In both patents the turbines are coupled to the rotors of the generators. The maximum possible power generated by the mud flow in this case, according to the Bernoulli's Theorem, is about 800 Watts and is strongly dependent on the mud flow rate [8]. Despite the fact that these devices produce sufficient amounts of power, they have some disadvantages. Due to the abrasive nature of the mud, the rotating mechanical parts of the devices wear out quickly, and maintenance is relatively intense and costly. In addition, the entire turbine-generator system obstructs the mud flow and decreases the efficiency of the mud circulation.

Another patent [10] proposes a different way of utilizing the energy of the rotating drill string downhole. The generator described in it has two components. The first component rotates along with the drill string, and the second rotates with respect to the first component. An eccentric mass is mounted inside the drill string and is coupled to the second component. This eccentric mass rotates in the direction of the second component as the drill string rotates. Thus, relative rotational motion is produced between the first and the second component and the generator outputs electrical power. This approach is limited with respect to the amount of generated energy because it fully depends on drill string rotation.

B. Vibrational energy sources

Vibration is another powerful downhole energy source. Vibrations are caused either by the mud flow [6, 11], by the movement of the drill string, or by the variability of the drilled formation resulting in drill bit bouncing [12]. Vibrations from the drilling process are passed onto a magnetic element which is positioned relative to an electromagnetic coil. The mechanical movement of the magnetic element is used to generate electromagnetic force in the coil. In other applications, mud flow vibrations are used to exert stress on a piezoelectric element [13].

Two main types of vibrations take place in a drilling operation - longitudinal and torsional. They are produced in the drill string by the load variations at the drill bit and are usually controlled by dampening mechanisms. In one patent [12], such vibration-dampening and shock-absorbing mechanism contains multiple piezoelectric elements. They are responsive to the vibrations of the drill string and thus produce electrical energy. The amplitudes and frequencies of the generated electrical waves vary and depend on the source of vibrations. The frequency range is from 5 Hz up to 1000 Hz [17]. Maximum generated power ranges from 1 mW to 2000 W [18]. Bit bounce vibrations are the most powerful, reaching amplitudes of 1000 g and frequencies of 1000 Hz [17]. According to previously reported power calculations [18], 1200 Watts is the maximum possible power generated by this source. Its energy potential is higher than the energy obtained from the kinetic mud flow sources, but its limitations are imposed by the available space in the drill string (see Table 1).

C. Thermal energy sources

It has been proposed to utilize thermoelectric devices for generating electric power downhole [7]. Temperature gradients (or differential ΔT) present in the well are used by such thermoelectric devices to produce voltage potentials across their output terminals. Two thermocouples are situated at different temperatures. The first of them is exposed to higher temperature and the second - to lower temperature. The electric power generated by such thermoelectric device is used to either recharge battery packs located downhole, or to directly power electrical devices and systems [7]. The average temperature differential in downhole conditions could reach 120° C. Electrical power generated by a single unit is less than 10 mW for ΔT = 120° C. This amount of power is far less than the necessary to autonomously supply any downhole electronics and can be utilized only for partial downhole battery recharging.

D. Electrostatic energy sources

Apart from being a source of kinetic energy, the mud flow downhole can be utilized as a source of electrostatic energy [15]. The flow of a non-conductive hydrocarbon-based fluid with relative electric permittivity between 2 and 40 creates an electrostatic potential between the flowstream and a tubular element located on the inside of the drill string. Electrical energy harvesting from this electrostatic potential takes place via a ground electrode in contact with the flowstream and another electrode in contact with the described tubular element. The obtained electrostatic potential is at least about 0.5 mV and can even reach about 50 kV. However, achieving this broad range of generated voltages would necessitate the utilization of many generating elements. This fact and the demands for specially designated rough-textured surface of the inner side of the tubular element make it difficult to predict the feasibility of such a complex system downhole. The generated power is not disclosed [15]. As explained in the description, a group of downhole devices draws power from an electrical storage device – a battery charged by the harvested electrical energy. Therefore, this type of harvester cannot autonomously and permanently satisfy the power needs of the downhole electronics.

E. Chemical energy sources

The chemical way of supplying energy downhole [16] differs a little from the concept of utilizing batteries. This approach makes use of extensively different chemical reactions than those taking place in conventional batteries. Its main advantage is that it can provide the desired amounts of electrical energy in a broad temperature range [16]. The claimed energy potential obtained from a fuel cell employing a chemical reaction involving hydrogen and oxygen can reach up to 2 kWh [16]. However, the need for refueling the cells is an imperative procedure similar to battery recharging. The complicated operation of such fuel cells and the specific fuel cell demands related to refueling make this electrical energy generation approach hardly applicable downhole. On the other hand, this huge amount of generated energy is more than sufficient for supplying modern downhole electronics.

Transformation of available downhole power sources into electric voltage

The voltages generated by the reviewed approaches are alternating and must be rectified and conditioned in order to supply the downhole electronics. Nowadays, precise conditioning electronics replaces uncontrolled rectifiers [19]. This is required due to the stricter low noise demands of modern electronic navigation and information-gathering equipment for horizontal drilling [20 - 23]. Such electronics withstands high temperatures of up to 200º C [24] and offers modern power management of the entire downhole information and navigation monitoring system. This helps to reduce the consumption of electrical energy downhole to the range of ten of Wh [25, 26] and to achieve reasonable power generation from a fully autonomous power supply downhole.

New ideas

Consideration for some untraditional ideas for energy harvesting could bring about the right solution for a radical change in the downhole electric power supply problem altogether. One of these ideas is not new and is well known as radioisotope thermoelectric generators [27]. They generate electrical power by radioactive decay. The heat released by the decay of a radioactive material is converted into electricity by the Seebeck effect using an array of thermocouples. Their feasibility has been tested in many industrial areas and even as power sources in satellites and space probes. The results are promising. Similar to this is the approach used in a recent patent application [28]. According to the description, a radioisotope thermoelectric generator emits heat from the core to the thermocouple to produce electricity that might be stored in an energy storage device, or used to power electronic components. The applicability of such concepts in downhole conditions, however, needs proof in situ.

Some other emerging ideas are attracting interest, but they need more thorough research and comprehensive feasibility studies. Another patent application [29] describes a high-efficiency energy source using the quantum mechanics process of electron tunneling. This energy source is sufficient to autonomously power-supply small electronic devices downhole. Nevertheless, the entire system makes use of a battery to operate, which makes it inconvenient.

Discussion

The main aim of a downhole electric energy supply is to power the MWD/LWD electronics in the most efficient way. An information flow in the range of 8 - 100 bps should be continuously transferred to the end point of the MWD/LWD data acquisition system on the surface [30]. Contemporary systems for communication and transmission of data in a borehole are mud pressure pulse telemetry systems, electromagnetic methods, insulated conductor or hardwire systems, and acoustic methods [12, 30]. The necessary power for collecting and transmitting this information is in the range of hundreds of Watts. On the other hand, numerous energy sources downhole offer significant possibilities for delivering this energy. However, the main problems of energy harvesting downhole are related to efficiency and convenience in the process of power transformation, and still remain unresolved. Many of the discussed approaches could not match the demands of the existing industrial standards or would create complications in the smooth operation of the drilling equipment. All of these concepts show significant deficiencies in terms of long-term applicability. This is a clear indicator that mature technology for effective in situ power supplying downhole is still lacking.

The combined utilization of many different energy sources or the parallel use of energy generators and batteries in one system are possible solutions for optimizing downhole electrical energy supply. The success of such compromise approach strongly depends on the straightforwardness of its industrial applicability.

On the other hand, due to the severe vibration and high temperature conditions downhole, special measures should be taken for the durability and the thermal insulation of any downhole device. The device should have thermo-isolating shield and special protection against vibrations in order to function reliably. All these issues additionally complicate the implementation of sophisticated but effective power generating systems downhole.

Conclusions

This short review demonstrates that the best method for continuously generating electrical power downhole in-situ is still to emerge. Such a method should avoid storing energy in a battery placed downhole, since it is difficult to recharge it there. The method should also not require that power be transmitted from a remote location via one or more conductors positioned in the production mud flowpath of a well. There is a need for a self-sustaining electric power source to supply with energy all electronic instrumentation downhole. Improvements in the energy harvesting techniques downhole, as described by the discussed technologies, are insufficient and may not bring the convenience and efficiency desired during the entire downhole operation. The complexity of their practical implementation makes them hardly feasible. Nevertheless, the energy generated by some of the proposed devices is enough to partially recharge batteries, thus extending downhole battery lifespan. However, an autonomous electrical power supply, continuously generating electrical power in the range of at least 40 - 60 Watts, remains an unfulfilled promise. This amount of power can satisfy the needs of modern electronic navigation in horizontal drilling processes. Thus, downhole information exchange would become more versatile and the cost of oil exploration would be significantly reduced. Intensive research in creating a versatile and autonomous power supply for horizontal drilling processes is still in progress.

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