Energy Harvesting Under Harsh Conditions: Towards a Safe Oil & Gas Industry (Energy4Oil)

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ABSTRACT

Environmental and safety sensing is becoming of high importance in the oil and gas upstream industry. However, present solutions to feed theses sensors are expensive and dangerous and there is so far no technology able to generate electrical energy in the operational conditions of oil and gas extraction wells. In the Energy4Oil project it was developed and tested for the first time in a relevant environment a pioneering energy harvesting technology based on nanomaterials taking advantage of fluid movement in oil extraction wells to power monitoring systems with locally harvested energy towards self-power systems.

Keywords: Triboelectric nanogenerators; Harsh environment; Oil & gas, Energy harvesting.

1. INTRODUCTION

Obtaining data in harsh environments is particularly critical, especially in the oil and gas industry that needs to constantly monitor crucial safety and environmental parameters in drilling wells in order to prevent disasters such as oil spills, fires or, ultimately, explosions. However, electrical power in oil and gas wells is so far supplied downhole via tubing encapsulated cables (from the surface) or in-situ via batteries. Both scenarios come at high risks: long lengths of cable lead to reliability concerns due to possible ruptures, and battery replacement involves complex and costly underwater operations. On average, an offshore oil well must stop its production once every year due to battery maintenance alone. This single shutdown can cause a chain reaction in terms of costs: less barrels being produced per year, more losses in production, raising in unit operating costs and an increase for environmental risk.

According to the Fuel Report 2020 by IEA, global oil demand will grow by 5,7 mb/d over the 2019-25 period [1]. Also, according to the UK Continental Shelf Production Efficiency (UKCS-PE) report in 2018, total UKCS production potential in 2017 was 800 million boe. It also stated that if there was a 1% improvement on efficiency, meaning a 12 million extra boe per year, and a 5% down in production losses, saving 10 million boe in that year, that would represent a market opportunity of more than 700 millions of dollars per year at an average of a 70-dollar barrel. The technology developed in this project will address these challenges faced by the industry in downhole power generation for drilling platforms.

Thus, under this ATTRACT phase 1, the Energy4Oil project aimed for an innovation step in the implementation of energy harvesting devices in industrial environments, underlining the following objectives:

- To develop a new energy harvester, based on emergent nanomaterials, to convert the fluid mechanical energy into electrical power in high temperatures and pressures scenarios.
- To assemble a versatile closed-loop testing system in which oil flows at velocities up to 60 l/min and pressures up to 6000 psi.
- To integrate the developed energy generation system on 2.5-inch diameter stainless steel tubes for dynamic tests.
- To advance the proposed technology from TRL3 to TRL4-5.
- To develop a business model focusing on the production of downhole power generation products for the upstream Oil & Gas industry.
- To assess the applicability of the developed energy harvesting technology on other relevant industrial and remote environments, including the transforming, automotive, smart water systems, or smart agriculture.

2. STATE OF THE ART

Motivated by the constant monitoring and management of a range of sensors, a search for technologies capable of downhole power generation is still pursuit. Most designed solutions are inspired on impellers and electromagnetic generators [2]–[5], driven by the mud flux, facing serious problems of mechanical parts failure and low efficiency, occupying the cross section of the drill extraction pipe. [6], [7]. The helical or toroidal approach to harvest energy from fluid flux is something being studied as it only used a small peripherical ring [8]–[12]. Another approach [13]–[15] uses piezoelectric energy harvesters to generate enough power to feed electronic devices even at low fluid flux from 20 to 40 l/min when excited by fluid vortexes [16].

Triboelectric nanogenerators (TENGs) have also shown to be able to harvest energy from pipeline vibration [17], [18]. Thus, they started to recently be tested for applications related to the Oil & Gas exploration. For downhole environment, Ref [19] proposes a TENG that can harvest energy from drilling vibration and simultaneously act as a sensor to measure the vibration frequency. On the other hand, inanoEnergy [20] recently developed the first TENG able to harvest energy from the direct contact with Oil & Gas at high pressure (up to 830 bar) and temperature (up to 120ºC).

So far, a fullly integrated system tested under continuous oil flow with harsh conditions was not developed/reported. Thus, Energy4Oil appear as a pioneering concept able to surpass/overcome these barriers towards a novel energy harvesting system able to operate in harsh conditions (high temperatures, high pressures, remote locations), to increase safety and decrease operational costs in oil wells and tested under controlled but simulated real conditions.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The use of nanotechnologies in power generation systems has several obvious advantages: they are small, light, efficient, flexible, and easily adaptable to remote locations. They can be used to feed various types of sensors [21]–[23], avoiding the use of energy cables, packer holes and flux obstructions. Also, by avoiding pressure drops and having a simplified integration, our approach is extremely advantageous when compared to most of the technologies reported in the literature so far.

The differentiation characteristics of the solution here proposed, could lead to major disruptions in the innovation chain. Therefore, this endeavour will allow us to introduce in the market highly efficient nano-generators for energy harvesting of fluid flux streams.

The main advantage of the Triboelectric Nanogenerator is the reduced thickness that can be down to a few millimetres which, together with a high flexibility, allow its applicability on pipe walls, reducing restriction on well bore mud extraction at reduced costs.

4. PROJECT RESULTS

Throughout the project, a novel solution capable of downhole power generation in harsh conditions was designed, architecture and implemented. Towards the goal of a TRL4-5, it was necessary to develop the energy harvesting prototypes and experimental setups operating in a continuous fluid flow environment, being one step closer to real working conditions on oil extraction wells.

1) Closed loop Oil Flux Test Bench

To test the nanogenerator we designed and assembled a test bench (Fig. 1) fulfilling the basic requirements for the intended testes (flow up to 57 l/min and temperature between 20 and 50 ‘C). The work bench allows the user to control the fluid flux from 10 to 100 l/min at low pressure rates. After the inhouse development and testing, the prototype will be subjected to more demanding conditions at X-rig facilities, where higher pressures and controlled temperatures will be added to the experiments.

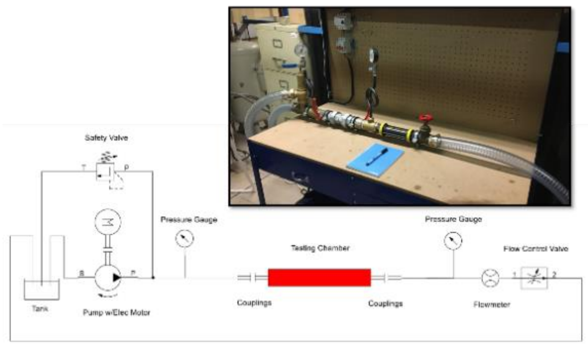

Fig. 1 - Schematic diagram of the Oil Flux testing bench.

2) Nanogenerator deployment

The developed nanogenerators are composed by a frame structure that holds and promotes the contact between the energy generation materials. The device could then be assembled inside of a pipe for testing. The triboelectric pair assembled follows the contact-separation topology [21], in which a stack of materials was mounted to convert mechanical energy from fluid motion into electrical energy. In order to maximize the electrical output and based on the tribo-polarities [22] two opposite materials were used taking into account the outputs and non-degradations under so harsh conditions. To each tribo-material a film was deposited to act as electrode.

The oil flow inside the pipe induces a vibration that causes a differential voltage between the electrodes, resulting in a current flow when the electrodes are connected through an external load. With this solution, it was possible to use the turbulent oil flow (representative of Crude oil extraction) to produce energy in a very low flow-restriction implementation.

3) Nanogenerator validation and electrical characterization in harsh conditions

To validate the prototype, it was tested on the assembled Oil Flux Test Bench. The device was fixed inside a steel pipe and tested under the following working conditions:

- Fluid: Lubrication oil (Shell Morlina S2 BL 10);
- Fluid Flow: 55+/-2.5 l/min;
- Fluid Temperature: 25ºC up to 50ºC;
- Chamber Pressure: 1.013 bar;
- Chamber interior diameter: 100 mm.

With these conditions and the device inside the test chamber, several tests with approximately 30 minutes of duration were performed. During each test, the generated voltage and current was measured using standard protocols available at inanoEnergy

Fig. 2a) shows the open-circuit voltage profile just before and after oil starts circulating, in which it is possible to observe the difference between the steady and dynamic stages. For such conditions, a maximum open-circuit voltage and short-circuit current, of 4 V and 750 nA wer reached, respectively.

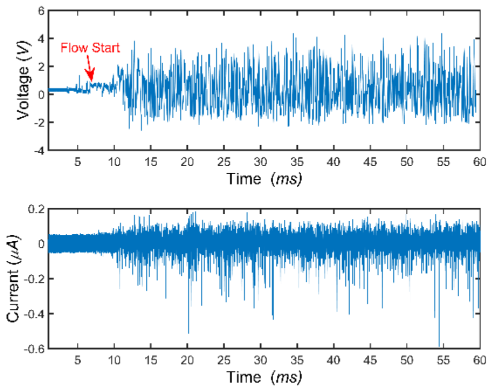

Fig. 2 - Open-Circuit Voltage and Short-Circuit Current.

As the energy produced by the TENG changes with the external load resistance, one needs to find the optimum load point that maximize the energy produced by the device. Therefore, the load resistance was varied between 100 Ω and 470 MΩ. Figure 4 and Fig. 4 shows the evolution of voltage, current and power with the load resistance, where a maximum power of 1.24 µW was reached for a 10 MΩ external load, representing a power density of 0.2 mW/m^2.

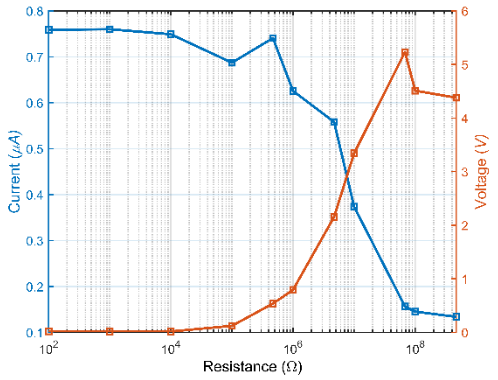

Fig. 3 - Dependence of the voltage and current output on the external load resistance

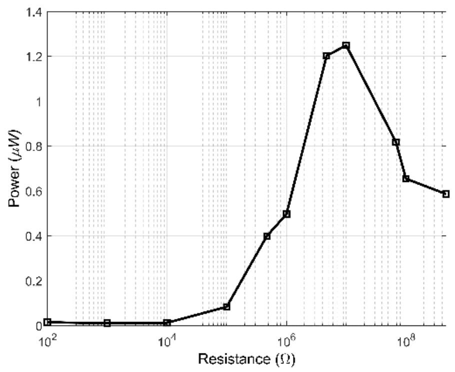

Fig. 4 - Dependence of the peak power output on the resistance of the external load.

5. FUTURE PROJECT VISION

Before the Energy4Oil (ATTRACT) project, inanoEnergy's technology achieved TRL3 with the experimental proof of concept. In phase 1, the ATTRACT funding allowed our technology to be validated in the lab, in a flow-loop system at static and dynamic conditions, achieving TRL4. By the end of the project period, the technology will be validated in an industrially relevant environment in dynamic conditions, at high temperatures and high pressures at XRig's [23] facilities, pushing to TRL 5.

5.1. Technology Scaling

To advance our TRL to 6-7 and prepare for a scaleup process, extra steps will be needed in terms of R&D, product and business development. Nevertheless, under our risk management efforts, we are already expecting the necessity to protect the prototype designed during the ATTRACT phase 1, to protect the electrodes to enhance output power and to validate its durability, exposing it to longer operation periods. This risk is of primordial importance, since in a mud extraction well there are rocks, crude oil, water, and a wide variety of particles that are extracted. Different configurations will be tested aiming to supply energy to a wide variety of sensors used on the oil and gas industry.

In the ATTRACT phase 2, the ultimate goal is to demonstrate the technology in an operational oil well, where key industry partners will be necessary, as well as enablers in terms of mass production (scale-up) and the Oil & Gas market.

5.2. Project Synergies and Outreach

In phase 2, we intend to maintain the current consortium and add new organizations to achieve TRL6-7. inanoEnergy will pursuit its work on nanogenerators and XRig can provide for advanced testing facilities. We will be looking for other ATTRACT projects focusing on low-power sensors and/or power electronics that would be interested in this application (or similar) and that will be key to achieve the project milestones. Furthermore, we aim to include a market enabler in the consortium, such as The Oil and Gas Technology Center (OGTC) [24], in the UK, and/or Repsol [25], in Spain, which has been constantly supporting inanoEnergy with contacts, updates and other assistance.

To facilitate the public dissemination, the consortium will recur mainly on a project website, social media, online webinars, conferences, and newsletters, based on our previous experience in phase 1. Thanks to the ATTRACT funding, it was possible to demonstrate our technology in one of the biggest conferences in the Oil & Gas Upstream market, the EPOCH 2020, originally held in the UK but hosted online this year due to COVID-19.

5.3. Technology application and demonstration cases

In phase 2, there will be three main demonstrations: a demonstration of the prototype in laboratory environment, a demonstration in a relevant environment and another in an operational well environment. All those experiments have the goal to show that our technology is capable of generating energy through the oil flux in high temperatures and high pressures, following the developments in phase 1, being able to charge a battery and to feed a small sensor used in drilling operations for long periods of time.

The successful demonstration will show that the implementation of this technology will avoid frequent well intervention for battery replacement in downhole environments in drilling operations. For the Oil & Gas industry, this means that cost and time would be decreased on well intervention while avoiding the need of recurring maintenance, which would increase the safety of workers and decrease the environmental risks of oil spilling. It would also avoid wasted production time, leading to more barrels being produced, less losses in production and decreasing in unit operating costs, making the drilling operation more efficient and safer.

5.4. Technology commercialization

From preliminary conversations with a potential customer from the United States, and since our solution seems to be a unique technology capable of solving critical problems presented in Oil & Gas monitoring systems, we clearly identified that our system is a “Problem/Solution Fit”, corresponding to IRL4. Furthermore, in phase 1, the energy harvesting technology had the interest from Shell, and it has received a strong evaluation from the industry panel in OGTC´s funding program in the UK.

The business plan was elaborated, and in phase 2 we will continue to outreach potential clients, investors, and industry leaders to facilitate commercialization. The participation on the conferences will be key to promote our technology, such as the EPOCH 2020 and 2021 MEOS (middle East Oil and Gas).

5.5. Envisioned risks

To the best of our knowledge there is no testing system readily available in the market that meet our needs. Thus, we will design and/or outsource our own custom testing platform to achieve TRL6. Based on our previous experience in phase 1, the delays related to supply and logistics is one of the biggest risks, which will be mitigated by a thorough project planning prior to phase 2 and the nomination of a project manager. There is also the risk of scaling-up into a market that is largely established. To mitigate this, we will partner with key industry players that will help us with contacts and suppliers. Also, the process of finding an early adopter for the final demonstration phase could take longer than expected, due to COVID-19 global situation with travel restriction. For that, online activities will take priority.

5.6. Liaison with Student Teams and Socio-Economic Study

Contribution to the scientific community and the development of new talents are key to the development of innovation projects. As a spin-off from the University of Porto (UP) and as a strong partner in its innovation platform, namely UPTEC [26], Faculty of Science and Faculty of Engineering from UP, inanoEnergy has been actively contributing to the development of education by offering internships, mentoring students in their masters and PhD thesis, and conducting advanced training in its areas of expertise [27].

Backed by its large experience, inanoEnergy will assign a team that will be in direct contact with the students. The goal will be to enable a strong collaboration and provide a meaningful learning platform. The team will organize training sessions, present the project and the partners in the consortium, show the development and the current state of the prototype and the final applications, and provide brainstorming sessions for the development of new applications. There will be periodic sessions with the students to develop new ideas and to possibly register them for future developments if it seems fit. We will also facilitate as much as possible the studies driven by the ATTRACT initiative with interviews, panels in conferences and other media platform.

5. ACKNOWLEDGEMENT

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