NOVEL GEOTHERMAL DRILLING FOR DEVELOPING HEAT EXCHANGERS: THE DEEPU PROJECT

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ABSTRACT

The technology envisioned in the “Deep U-tube heat exchanger breakthrough: combining laser and cryogenics gas for geothermal energy exploitation” project is expected to revolutionize the deep geothermal energy sector. A laser drill head is combined with special drill strings sustaining the coupled action of laser and cryogenic gas, responsible for melting, evaporating and cooling even the hardest rocks. The fine particles are transported to the surface in the gas stream. Specific temperature control analysis and innovative laser lenses, able to convey the heat and sustain multilateral drilling, guarantee liquefaction and vitrification of the rocks from the ground surface to significant depths. The technical feasibility of DeepU is demonstrated at the laboratory scale, and the specific objectives of the Project are: (i) develop an innovative lightweight drill string able to host the cryogenic fluid and the laser at the same time; (ii) develop specific temperature control analysis and innovative laser lenses able to convey the heat and to sustain multilateral drilling, (iii) determine the physical-thermal phenomena affecting different kinds of rocks in order to assess the borehole wall vitrification and integrity.

Keywords: laser drilling, cryogenic gas, deep heat exchangers, regulation, environmental and economic aspects

INTRODUCTION

Continuously renewable, CO_2-neutral, clean, affordable, and modern energy for the benefit of all people is the 7th of the United Nations Sustainable Development Goals (SDG). Geothermal energy (GTE), defined as the thermal energy stored in the earth, is considered a critical renewable energy source for the future, as c. 99 % of the earth’s mass is hotter than 1000 °C allowing GTE to be tapped through environmentally friendly carbon-neutral energy conversion (Horne 2012, Tester et al. 2006, Gupta and Roy 2006). The most commonly exploited resources at shallow reservoir depths (1-3km) represent a small fraction of the total recoverable energy that can be exploited at deeper depths. To meet modern society’s electricity and heating/cooling demands, innovative and emerging technologies must be developed to fully use the earth's geothermal potential (SET Plan 2018). GTE production is expected to grow steadily until 2050. Cost reduction and improved system performance, together with a better understanding of the geological conditions in which novel solutions for GTE production can be applied, are key factors in stimulating the uptake of GTE at the European and global levels (EGEC 2022, BP 2022). Understanding heat transfer and fluid flow in deep geologic environments over long periods (>20 years) remains a top priority for research and development (More and Simmons, 2013). Also, a drilling technology that is more efficient than the current one – from an economic and technological point of view, is crucial.

Besides facilitating a rapid transition to renewables, GTE plays a key role as it offers several advantages, e.g. its contribution to reducing the thermal needs of the residential sector thanks to its thermal technologies or its continuous and flexible production that can be switched between electricity and thermal generation in Combined Heat and Power (CHP) applications. Therefore, increasing the share of GTE in the energy mix is fundamental to developing national and European energy policies. Geothermal resources are conventionally divided into near-surface (shallow) and deep (Banks 2012, Huenges and Ledrou 2011). The former reach depths of 400 m and temperatures of c. 20 °C to 60 °C; they are used in combination with heat pumps or directly using geothermal heat in district heating networks. The latter, deep geothermal resources, have a temperature c. >100 °C at > 1km depth and are suitable for direct use of heat and electricity production. However, current deep geothermal technologies suffer limitations and disadvantages, among them: a) depth limitation (4-5km) due to the traditional drilling methods and evaporation temperature of the flushing water; b) earthquakes risk in case of hydraulic stimulation for permeability enhancement; c) high pumping costs for water circulation; d) risk of contamination in "open" water circuits (Manzella et al., 2019).

To overcome these limits and make projects economically viable, the DeepU technology focuses on demonstrating at the lab scale a U-shaped closed-loop system, i.e. physically isolated from the surrounding environment, through the temperature management of a combined laser/cryogenic gas drilling action. With a new, revolutionary, intelligent temperature management control system tested in the laboratory, the project will use a laser-beam propulsion drilling method and a cryogenic gaseous flushing medium to realize a heat exchanger consisting of two vertical and one horizontal tube section (U-shape). The tubes will be connected at a right angle by re-directing the vertical laser beam by 90°. The use of laser & cryogenic gas will form a glazed layer on the borehole walls, allowing an underground closed-loop system to immediately develop after drilling without requiring further casing activities. This technical solution will also favor the gravity pump effect during geothermal exploitation. If successful, the DeepU technological solution will contribute to realizing ultra-deep geothermal heat exchangers at >4km depth.

A laser drill head is combined with special drill strings sustaining the coupled action of laser and cryogenic gas, responsible for melting, evaporating and cooling even the hardest rocks. The fine particles are transported to the surface in the gas stream via the earth tube required for the geothermal heat exchanger. Specific temperature control analysis and innovative laser lenses convey the heat and sustain multilateral drilling. In addition, gases have to be kept cryogenic over a long distance. A press container has been set to perform the first laboratory tests with the novel lightweight laser and gas processing drill head and was equipped with monitoring devices. The drill-head prototype has been realised, combining the laser system with a novel drill-string design that can sustain the coupled action of laser and cryogenic gas. With a current laser setup, spallation is the most efficient process for rock penetration, while melting and evaporation are the secondary processes. The spallation is supported by the cryogenic gas flow that efficiently removes spalled particles. The fine particles of drilled rocks are ejected to the surface in the gas stream via the borehole annulus. An optical camera and a thermo-camera monitor the process.

The meticulous optimisation of laser parameters and experimental setups, coupled with microscopic examinations of drilled rocks, has revealed macro- and micro-scale phenomena that contribute to the successful development of this innovative drilling method. The project also analyses the exploitation potential and economics of the developed drilling technology utilising numerical simulations calibrated by the laboratory data. Furthermore, the legislative aspects and environmental standards related to the proposed solution are also assessed. The high-risk innovation presented in DeepU has the potential to make geothermal energy systems accessible anywhere in a targeted and demand-oriented manner, offering a complementary approach and an alternative solution to traditional energy storage and production, decentralizing the power supply also in areas where this is currently deemed uneconomic.

EXPERIMENTAL STUDIES

Cryogenic Gas

Various trials and tests are foreseen in order to achieve the main target of a lightweight drill string while keeping the cryogenic gas in the liquid state over a long distance within a drill string, to cool the laser drill head in the borehole where temperatures of over 1000°C prevail. This innovative drill string will also have to guide a laser beam in the middle of the drill string to the bottom of the borehole. The trials will test different gases and materials and also different ambient temperatures to better define the gas flushing medium for geothermal deep drilling, that have also the fundamental purpose to carry the “cuttings” to the surface.

We have investigated four different gases that could be used in the DeepU project, i.e., three noble gases (argon, krypton, helium) and nitrogen, which is abundant (78%) in the atmosphere. To consider a gas for this project, it must remain in the liquid phase for a very long distance under a great range of temperature and pressure conditions.

Table 1: Critical temperature, triple point temperature, boiling point temperature, melting point temperature and critical pressure values for the four cryogenic gases considered(.)

Gas	Critical temperature (CT)	Triple point temperature	Boiling point temperature	Melting point temperature	Critical pressure (absolute)
Argon (Ar)	-122.29 °C	-189.35 °C	-185.87 °C	-189.35 °C	48.98 bar
Krypton (Kr)	-63.8 °C	-157.39 °C	-153.37 °C	-157.4 °C	55.20 bar
Helium-4 (He)	-267.96 °C	-270.98 °C	-268.93 °C	-272.2 °C	2.274 bar
Nitrogen (N)	-146.958 °C	-209.999 °C	-195.795 °C	-209.9 °C	33.958 bar

Gases can be converted to liquids by compressing them at a suitable temperature. However, when the temperatures rise, maintaining liquefaction becomes more and more difficult as the kinetic energy of the particles that make up the gas also increases. Beyond the critical temperature (specific for each gas), the liquid state is impossible. Therefore, every effort must be made to ensure that the liquid gas in the cryogenic pipes heats up very, very slowly. The critical temperature (CT), the critical pressure (CP) and the triple point (TrPo) for each gas (Table 1) play a major role. The CT is the temperature at and above which a gas cannot exists as a liquid, no matter how much pressure is applied; the CP is the pressure required to liquify a gas at its critical temperature; the TrPo is the temperature and pressure at which the three phases (solid, liquid, and gas) of a pure substance can coexist in thermodynamic equilibrium.

In addition, the temperature difference (DT) between CT and the boiling temperature of each gas is a key factor in assessing the best temperature range for its use in the liquefied condition. For example, the DT value for krypton, argon, nitrogen and helium is 90 °C, 64 °C, 49 °C and 3 °C, respectively. Only if each liquid gas is kept within its specific temperature range, then can sufficient cooling volume prevent the DeepU drill head from melting in the borehole bottom.

Another essential factor that must not be ignored is the critical pressure (absolute). As shown in Table 1, the highest critical pressure of 5,500 kPa must be ensured for krypton, while argon, nitrogen and helium require 4,870, 3,390 and 227 kPa, respectively. Very few cryogenic tubes can withstand a pressure of 5,500 kPa, so argon and nitrogen are the two most suitable gases to be used within the drill string conceived in DeepU. In the coming months, further detailed investigations have to be carried out, especially on these two gases, about (i) their compatibility with the laser lenses, (ii) the cryotube materials used to realize the drill strings, such as stainless steel and fiber composites, and especially (iii) the interaction with different types of molten rock.

For the first laboratory tests, a drill string with an outer tube of 100 mm and an inner tube of 60 mm was designed and manufactured. The outer tube consists of a high-temperature stainless steel tube which can withstand temperatures of more than 1,000°C, and the inner tube is a low-temperature tube, which can withstand temperatures of -200°C (Bramfitt and Benscoter, 2001). Up to 8 cryogenic flexible tubes can be placed between the inner and outer tubes. Depending on the liquid gas required to cool the drill head, between 4 and 8 cryotubes can supply the drill head with liquid gas. The flexible cryotubes have a special coupling to prevent warming up the liquid gas in the coupling area and are outstanding at compensating for linear expansion due to temperature differences, making it easy to withstand high-temperature changes; In Figure 1 the schematics of the drilling head is reported. In the following months, several calculations and tests on the first drill string will be carried out to define at what depth the liquefied gases convert into the gaseous state, considering the upward gas flow generated by gas bubbles and a downward liquid gas flow pressure from above. In addition, the flow rate and power dissipation (W/m) in the cryotubes will be calculated and measured at various ambient temperatures. Moreover, different liquid gases will be pushed through the flexible cryotubes and the special Johnston couplings at varying pressures to test their strength and pressure resistance.

The next step will be to focus on the required wall thicknesses of the drill pipes as well as on the wall thickness and insulation of the cryotubes since they affect the overall weight of the drill string. The entire drill string's dead weight must always be kept in mind and considered in the whole design phase because the laser drill string is freely hanging on the drilling rig. An optimal lightweight solution is targeted to combine the issue of the logistic and management of the drilling components with the need to keep liquified gas in a liquid state over long distances, taking into consideration the current material availability and price levels of various liquid gases, especially in light of the existing global gas shortage.

Scaled model U-tube heat exchanger

To achieve the main objective of demonstrating the DeepU technical solution for deep heat exchangers, experiments are carried out in the project to examine the physical basis of the interaction between laser beam, cryogenic gas and rock material. The process states must be recorded in these experiments using suitable measured variables and appropriate sensor technology. Fraunhofer IAPT delivers extensive experience in high-power laser application, especially in rock fracturing by laser. The research institute provides its shipbuilding hall as a vast laboratory and a 30 kW fiber laser for the tests on rock. Since the rock is not only to be broken up in the new process but also completely melted by laser and then pulverized by the gas, a new processing head and a new drill string are required for the experiments. Fraunhofer IAPT is one of the leading institutes in the field of 3D printing and will use this technology to create the necessary components made of very heat-resistant materials such as titanium or Inconel. The laser and gas experiments will take place in a large metal box filled with stones or other soil formations. Simulation models for laser and gas interaction with rock material have to describe and predict the process flow for different rock types. Optimizing the process parameters, the drilling speed should be increased up to 20 to 30 meters per hour. That is at least ten times the drilling speed compared to conventional methods, which only reach about 1 to 2 meters per hour in hard rock (Anders et al., 2017). The speed increase will reduce the drilling costs to 1,000 Euro per meter for deep boreholes, i.e. to a quarter compared to the established methods.

Fraunhofer IAPT has realized the experimental set-up in a press container (Fig. 2). On the one hand, this large box serves as a safety enclosure for the laser machining process, and, on the other hand, it offers the possibility of compacting the soil with the pressing function if necessary for the tests. Initial results of the experiments show symmetrical and accurate drill holes with a diameter of approximately 90 millimeters in sandstone and 80 millimeters in granite. Surprisingly, these first process applications have already achieved projected drilling speeds of up to 20 meters per hour.

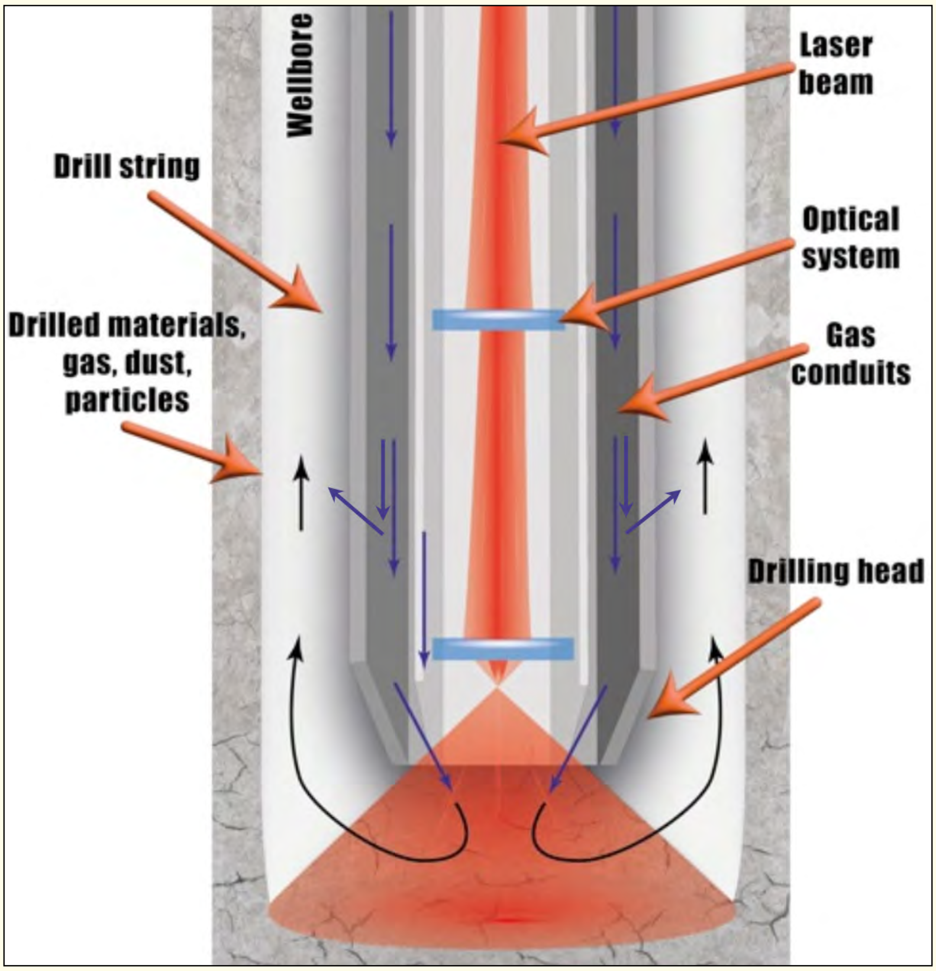

Figure 1. Schematics of the drilling head.

Figure 2: Experimental set up during a test with a granite slab (50x35x15 cm).

RESULTS AND DISCUSSION

Another fundamental research step is to analyze the thermal effects of the laser and cryogenic gas combined action on several kinds of rocks, both before and after exposure to severe thermal stress conditions (melting and cooling phases). On the one hand, it is essential to determine the laser beam impacts on the petrophysical characteristics of the tested rocks. On the other, to verify the state of vitrification along the borehole walls resulting from the cryogenic gas inflow. The overall thermal shocks induced on the samples will be analyzed to understand the change in the rock thermodynamic equilibria during melting and crystallization, also recurring to numerical simulation. In addition, the drilling residues (cutting material and gases) produced/released by the melting and/or evaporation phases will be characterized to assess the potential environmental, health and safety risk and the particle tendency to re-agglomerate, creating an obstacle to successful DeepU drilling.

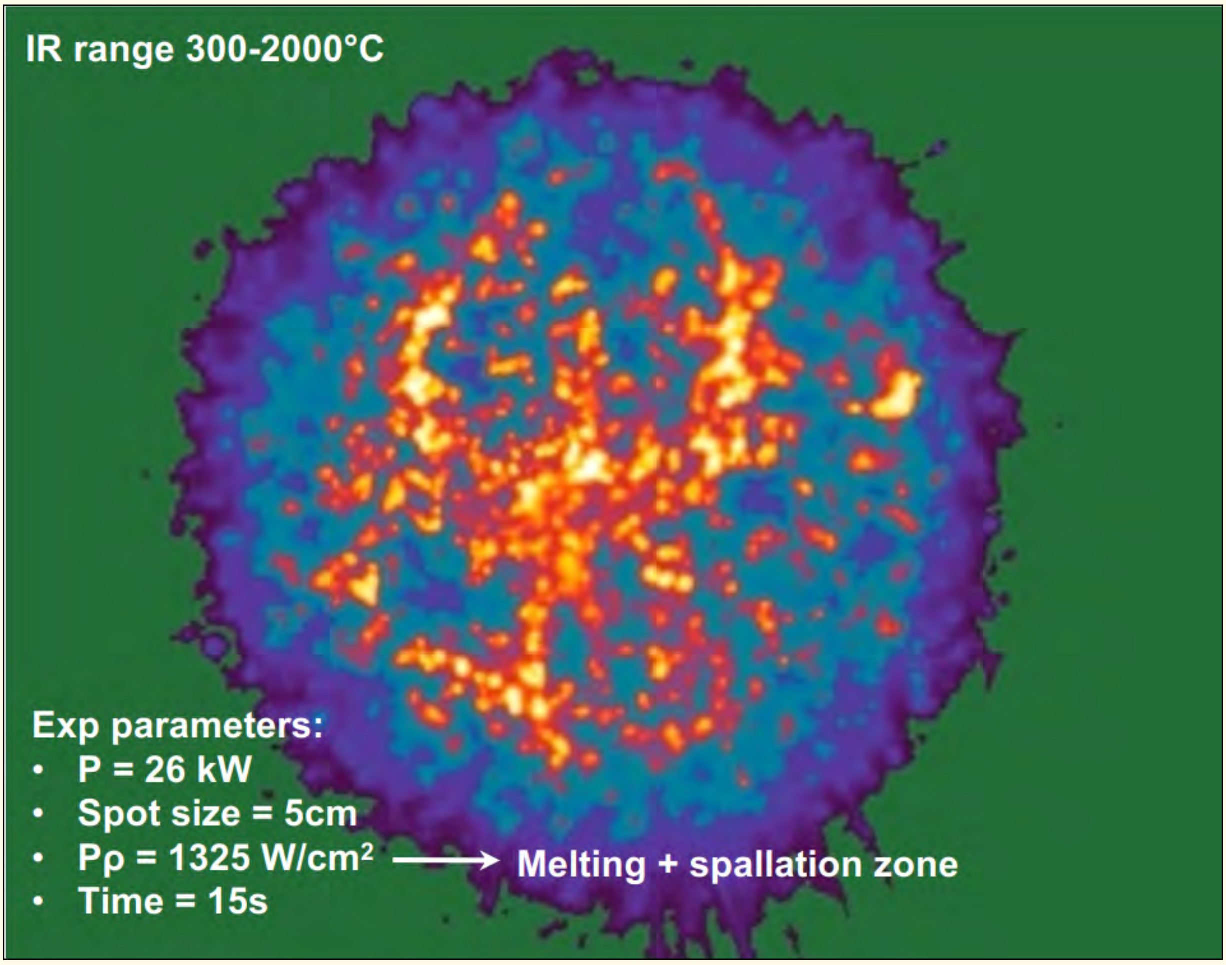

Figure 3: Thermal image of the drilling spot on a granite slab during one experiment.

The lithic materials will be analyzed by optical microscopy (OM) and electron microscopy (SEM-EDS) to characterize the mineralogical-petrographic and microstructural characteristics of the pre- and post-vaporizing/melting effects. X-ray powder diffraction (XRPD), solid-state NMR (MAS-SS-NMR), and vibrational spectroscopies (FTIR, Raman) will be performed on microvolumes of samples to fully determine the mineralogical nature, specific microstructural elements, and neoformation phases. Samples of granite, sandstone and limestone with the dimension of 500 x 350 x 150 mm are under testing at Fraunhofer IAPT. These three lithologies were selected as the first to be tested because they represent the hardest rocks (granite) to be drilled at deep depth, and the most common geothermal reservoir rocks (sandstone and limestone). The first tests were performed on granite and sandstone using only the laser beam and without cryogenic gas. Some crack fractures developed due to the thermal shock induced by the laser beam and the absence of confining pressure.

Up to now, six samples' blocks (2 granites, 2 sandstones, 2 limestones) have been prepared for further analysis. For each lithology, one block is made of fresh unaltered rocks from the quarry, and the second one undergoes laser drilling by the drill string and drill head prototypes already realized. The hole diameters obtained vary according to lithology and laser use. In this research phase, the rocks are melted only by the laser beam and are not yet cooled down by the cryogenic gas.

CONCLUSIONS

The first DeepU project results show the solidity of the proposed approach and indicate the effectiveness of the path taken in achieving all the set goals.

First of all, the technological developments taken in the DeepU project led to the design and manufacturing of the drill string able to convey the laser beam downwards (outer tube 100 mm, inner tube 60 mm), also considering possible alternatives to convey the cryogenic gas flow (i.e. flexible cryotubes). In addition, four gases (argon Ar, krypton Kr, helium He, nitrogen N) were considered potential cryogenic gas for the innovative DeepU technology and Nitrogen was selected.

The laboratory set-up for rock melting/vaporization and vitrification was prepared. A container is adapted as a safe housing to run laser experiments. The container, equipped with side windows for visual inspection of operations and housings for sensors and monitoring devices, is ready to host rock samples to be tested, the drill string with laser and the gas processing head. In addition, the first tests concerning granite, limestone and sandstone samples have already been performed.

Suitable rocks for lab tests were selected, and the laboratory test devices are defined to be used later in the project. The sample blocks, drilled up to now only by the laser action, will be analyzed to characterize the petrophysical and thermal behavior of the samples before and after laser interaction; in Figure 3, a thermal image of granite rock during laser drilling is reported.

Legislative and regulatory aspects and standards for gas flushing medium in deep drilling, factors related to drilling, well completion and deep U heat exchangers have been tracked down. They will be explored in depth in the next future.

Given this background, the near future is expected to provide more fascinating results through research and planned technological advances, including characterization of what happens inside the rock once it undergoes melting.

As results of the first batch of experiments, we have the Rate Of Penetration (ROP) for 3 different rock type, both dry and water saturated, reported in Table 2, that confirm the large possibilities and future impact of the Laser Drilling technology in geothermal applications.

Table 2: Summary of laser drilling experiments at 26kW, 5 ⌀cm, N2 flux. # - H_2O saturated sample.

Lithology	ROP (m/h)	SE (kJ/cm^3)
granite	10,0	5,6
sandstone	14,8	4,1
limestone	2,5	86,7
limestone#	4,5	16,3
sandstone#	25,1	2,3

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