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THE PERMEABILITY OF LASER DRILLED LATERALS IN SANDSTONE RESERVOIRS

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ABSTRACT

The aim of our research is prove the performance of a recently developed economical and environmentally safe technology using subsurface laser drilling. Instead of the already tested and known laser spallation drilling technology another method is under development which based on the melting of the subsurface geological formations and the removal of debris. This technology may help both the well completion and rework tasks in fluid mining especially in geothermal energy and hydrocarbon production but also in special remediation works at contaminated sites.

The drilling procedure was performed using sandstone samples originated from the Upper Pannonian reservoirs of the Great Hungarian Plain in high pressure chamber.

Current tests were performed to determine the permeability of the system surround the laser completed holes and to compare them with permeability of the original „virgin" rock samples. There was a testing and drilling methodology developed in Hungary that was applied on hundreds of samples by the laser engineering company in Malta using their own laser device. The evaluation of test results may help the developers of the laser drilling technology to fine tune their developments on design and manufacturing laser driven boring heads.

Laboratory measurements indicate that this innovative new technology will help save reservoir integrity and will increase drainage area resulting in low pressure gradient both production and injection wells.

INTRODUCTION

The extraction of all fluids from the pore volume of any structure has a special importance in fluid mining, especially drinking water supply, geothermics and even in remediation *(Szanyi & Kovács, 2010)*. At all applications the need to produce the fluids using the smallest gradient is essential, therefore all developments that makes the reduction of well or production unit losses possible are of high importance. The laser drilling technology offers us a new possibility on forming subsurface structures since during the drilling the melted material forms the possible in situ "screen" of the tube *(Bajcsi et al., 2014)*. The drilling procedure is now on technical readiness level 2–3, therefore in situ tests are not possible now, but the drilling procedure can be performed on small samples in high pressure chamber or on real size samples in normal pressure conditions. The paper deals with the laboratory permeability tests performed.

PRINCIPLES OF LASER DRILLING TECHNOLOGY

Recent developments on the fields of laser technology enables us to use low energy loss high power laser devices (HPLD) even in large depths via the new standard high carrying capacity optical fibers.

The HPLD will utilize cutting-edge, underbalanced laser well completion and rework technology in fluid mining, including oil and gas as well as the geothermal industry. The system is comprised of a high power laser generator and a specially designed directional laser drilling head. The laser head is attached to coiled tubing or an umbilical system to maximize production and to carry out special jobs.

The laser tool will superheat the subsurface formation, melt the target material and will remove the molten debris while the borehole is being drilled *(Figure 1, Bajcsi et al. 2015 in press*).

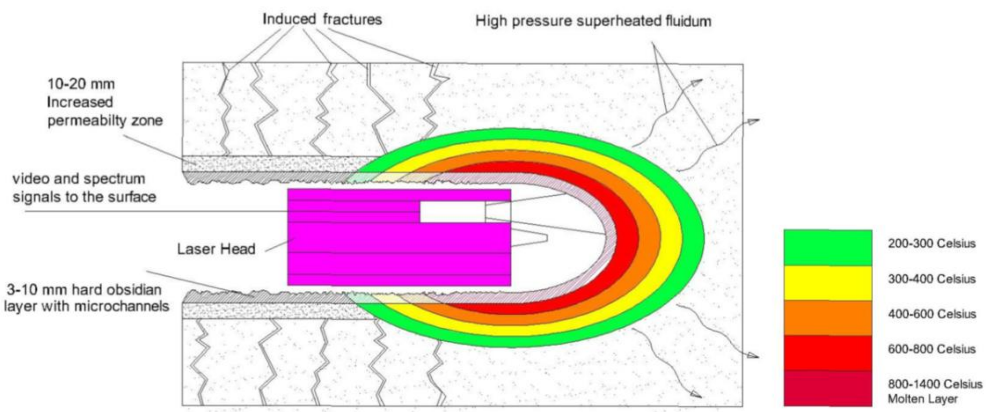

Figure1. Scheme of laser drilling procedure

The technology allows the operator to adjust the permeability of the borehole wall. The result of this process is a highly permeable approx. 1 – 2 inch diameter lateral pointing into any desired direction *(Figure 2),* with large active surface to increase either water production yields or to reduce the pressure gradient nearby the opened section of the well.

Laser drilling complies with standard industry safety standards and rules and fits into existing drilling equipment and offers an in-situ, real-time fully controlled procedure with video and spectroscopy feedback to the operator, with no wearing parts, no chemicals and low maintenance while maintaining formation integrity and environmental safety.

In this phase of the development effort the laser technology is especially well suited for economically drilling short laterals from existing wells in a single work phase, drilling through the casing, cement and the formation as well, with one tool in and out. Elements of the technology are patent pending.

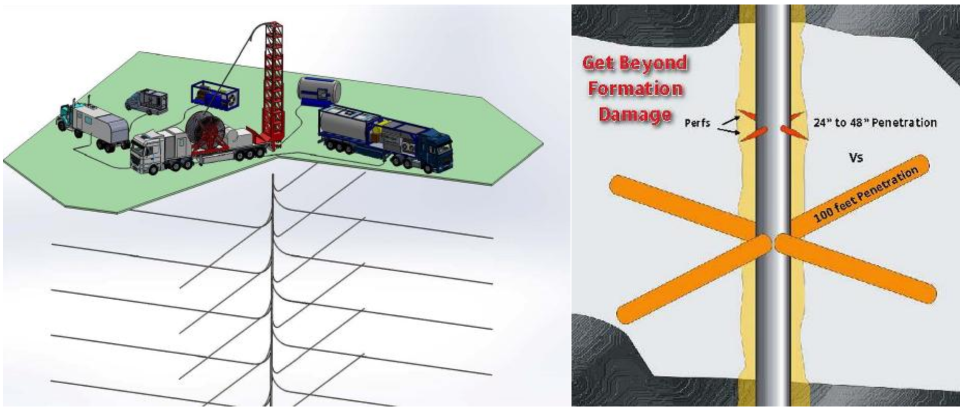

Figure 2. Laterals in any desired direction can be drilled using the heads (Bajcsi et al, 2015 in press)

PERMEABILITY TESTING METHODOLOGY

The permeability tests were performed on cylindrical samples using radial infiltration. The sample size was 54 mm diameter with 40 mm cylinder height that fits the standards 150 bar high pressure chamber of the laser testing company. There is a possibility to make pressure difference between the two sides of the sample that is to simulate underbalanced or over-pressurized drilling conditions.

At the beginning the samples were drilled out from large diameter oil industrial samples and cut to the predefined size. Using a special tool a small diameter hole of 8– 10 mm was drilled into the centerline (axis) using the traditional drilling technology. The permeability of the sample was tested using air, organic fluid and water. The organic fluid consisted of short carbon chain aliphatic hydrocarbons of a constant mixing ratio. Before, between and after the tests the pore fluid was pressed out or vaporized form the pore volume that was proven by scaling of the samples.

After the test of the “virgin” samples the laser treatment was done by the laser engineering company. A laser device with 1.5 kW laser beam power was applied until the drilling hole of the required size was formed. Due to technical reasons to avoid the damages of high pressure chamber damages and to keep ± 5 bar pressure difference on the samples during the drilling the mechanically drilled hole was filled up using the drilling powder produced during the mechanical drilling procedure.

After the laser treatment the permeability of the sample was once more measured using air, organic liquid and water.

To make the permeability tests a self developed pressure chamber was used, which contained seven sample holders. The tests were completed at constant hydraulic gradient (constant head) for the seven parallel measurements using 50– 200 kPa overpressure in the pressure container. The applied overpressure was reverse to the average permeability of the samples; the pressure range was set to highest measurement error reduction. The circle shaped walls of the samples were clogged using high deformable silicon plates and plastic silicone gel therefore the infiltration from the chamber could happen only on the side-walls.

The mechanically or laser drilled holes formed the drainage path from where the liquid or the air was led out and its volume was continuously measured.

Based on the well formula the yield (Q) of radial flow of v Darcy velocity through an area A, in a medium of K hydraulic conductivity can be calculated using the r radial distance as follows *(Figure 3)*:

$$Q = A \cdot v = 2\pi \cdot r \cdot l \cdot K \frac{dh}{dr}$$

or after integration:

$$Q = 2\pi \cdot l \cdot K \cdot \frac{H - h_0}{\ln \frac{R}{r_0}} \cdot$$

This makes possible to calculate the K hydraulic conductivity or k permeability of the sample based on ν kinematic viscosity of the liquid and ρ_v liquid density and the g gravitational acceleration:

$$K = \frac{Q \cdot \ln \frac{R}{r_0}}{2\pi \cdot l \cdot (H - h_0)} \quad \text{and}$$

$$k = \frac{K \cdot \nu}{\rho_v \cdot g} = \frac{\nu \cdot Q \cdot \ln \frac{R}{r_0}}{2\pi \cdot l \cdot (H - h_0) \cdot \rho_v \cdot g},$$

respectively. The meaning of the letters is shown in *Figure 3*.

After the laser drilling a rigid wall is formed from the melted material that has an approximately constant thickness. As previous investigation proved that the permeability changes of the non-melted region is irrelevant, therefore the total hydraulic head using the R total and R_0 melted range radius can be written into the form:

$$H = H_0 + \frac{Q}{2\pi \cdot l \cdot K_1} \cdot \ln \frac{R}{R_0} = h_0 + \frac{Q}{2\pi \cdot l \cdot K_2} \cdot \ln \frac{R_0}{r_0} + \frac{Q}{2\pi \cdot l \cdot K_1} \cdot \ln \frac{R}{R_0} \cdot$$

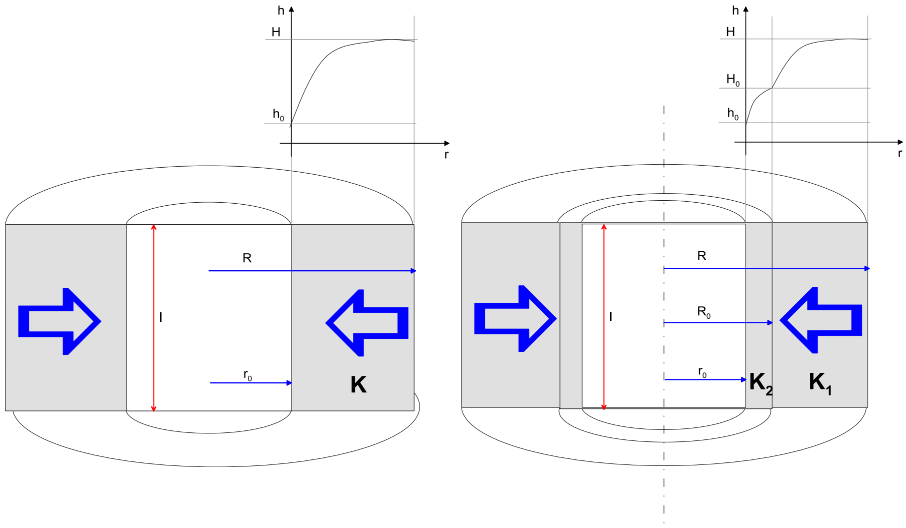

Figure 3. Calculation scheme of permeability in homogeneous and axially symmetric inhomogeneous system

The hydraulic conductivity and the permeability of the melted zone can be calculated as follows:

$$K_2 = \frac{\ln \frac{R_0}{r_0}}{2\pi \cdot l \cdot \frac{H - h_0}{Q} - \frac{\ln \frac{R}{R_0}}{K_1}} \quad \text{and}$$

$$k_2 = \frac{K_2 \cdot \nu}{\rho_v \cdot g} = \frac{\nu}{\rho_v g} \cdot \frac{\ln \frac{R_0}{r_0}}{2\pi \cdot l \cdot \frac{H - h_0}{Q} - \frac{\ln \frac{R}{R_0}}{K_1}}.$$

The above described testing methodology has several approximations: First of all the melted surface may have irregular surface *(Figure 4)*, moreover the interface between the melted and undisturbed zone has a given extent *(Figure 5)*. The biggest measurement problem is that in the reality the heat shock creates numerous micro and macro-fissures in the sample *(Figure 6)* that are prescribed flow paths that are included into the calculations. Previously some plug samples were investigated where the plate perpendicular to the axis was melted and laser treated *(Bódi, 2014)*. In this case a smaller heat shock was applied and therefore the forming of heat induced fractures was almost negligible. Based on the permeability measurements it was stated obviously that the extent of the permeability change remains within 25 percent in most of the cases, which has no harmful effect on hydraulic well performance *(Bajcsi et al., 2015 in press)*.

In our case the investigation of over two hundred samples was performed to analyze the probabilities of different phenomena.

Figure 4. Laser drilled holes with melted smooth and bubble containing surfaces with and without heat shock induced fractures

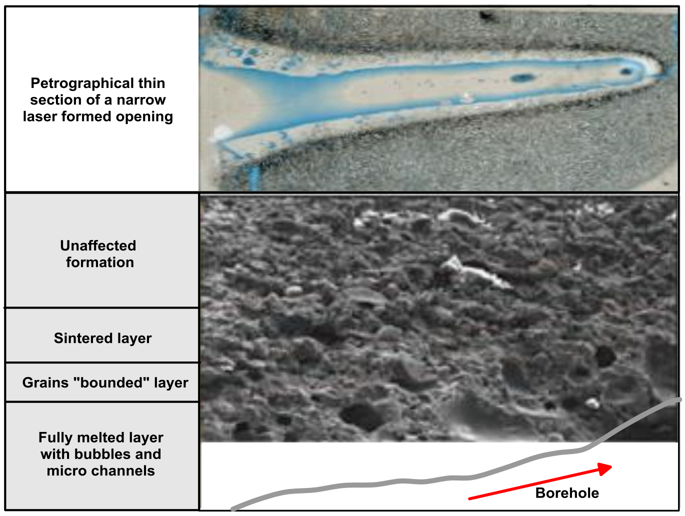

Figure 5. The optical microscopic (above) electron microscopic (below) image of the laser drilled hole's surroundings

PERMEABILITY MEASUREMENT RESULTS

During the test phase the permeability of several hundreds of samples were measured. Besides air, water and aliphatic hydrocarbons were used as test liquids. The permeability of "virgin" or original samples that were collected from the lowest permeability sections of the sandstone reservoir was measured in the range of 0.01–200 mD *(Figure 7 and 8)*.

Surprisingly after the laser treatment the average permeability of the samples was increasing by a factor 1.5– 4. In some cases discrete fractures could be observed in radial directions but there were several samples where only invisible micro-fissures were formed due to the treatment. The increase of permeability was both due to the matrix and both to the fractures therefore this was called later as apparent permeability.

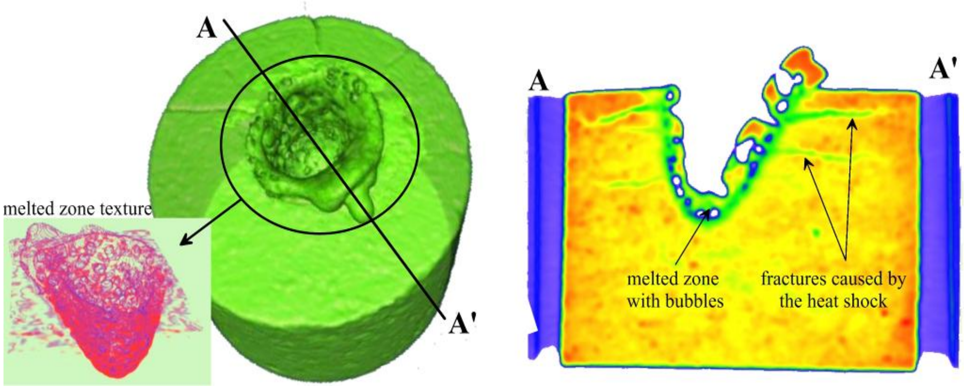

Figure 6. The 3D structure and the cross section of the laser treated sandstone sample on computed tomography images

Only in less than 5% of the cases the fractures did not reached the sidewall of the samples, in these cases a slight reduction of the permeability was observed. In a few cases the increase of permeability reached the 2– 3 order of magnitudes, these are generally not plotted due to technical reasons.

Based on the experiences the range of heat shock induced fractures is larger than 2 centimeters from the wall, which is coherent to the previous studies and CT investigations. Based on the test results it was proven that a 1 inch diameter laser drilled borehole acts as an approx. 3 inch diameter drainage system which has large side wall stability. During the tests no sand infiltration or leakage was experienced even at large hydraulic gradients (I > 600– 800 m/m). The tests showed that the laser drilled lateral may function even at unfavorable geological and geotechnical conditions as wet silty formations or soils liable to liquefaction.

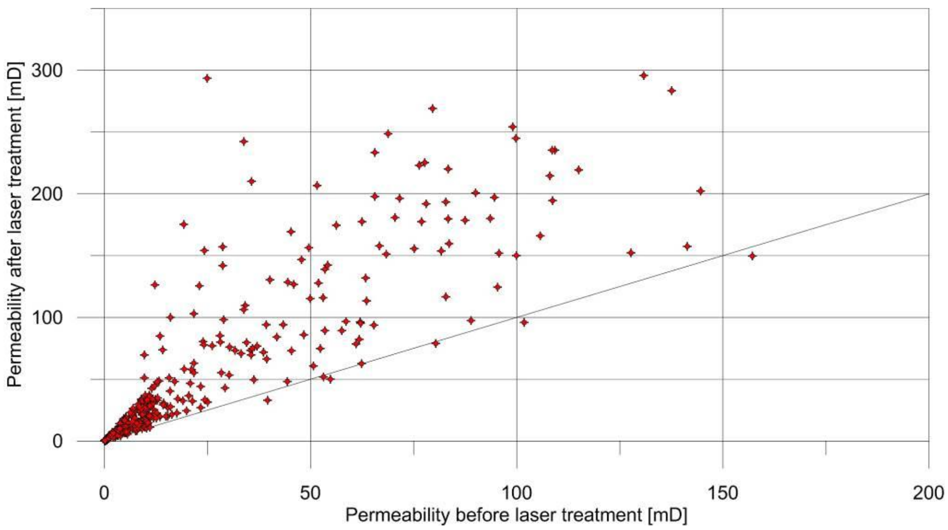

Figure 7. The apparent permeability increase due to heat shock induced fracturing caused by laser drilling

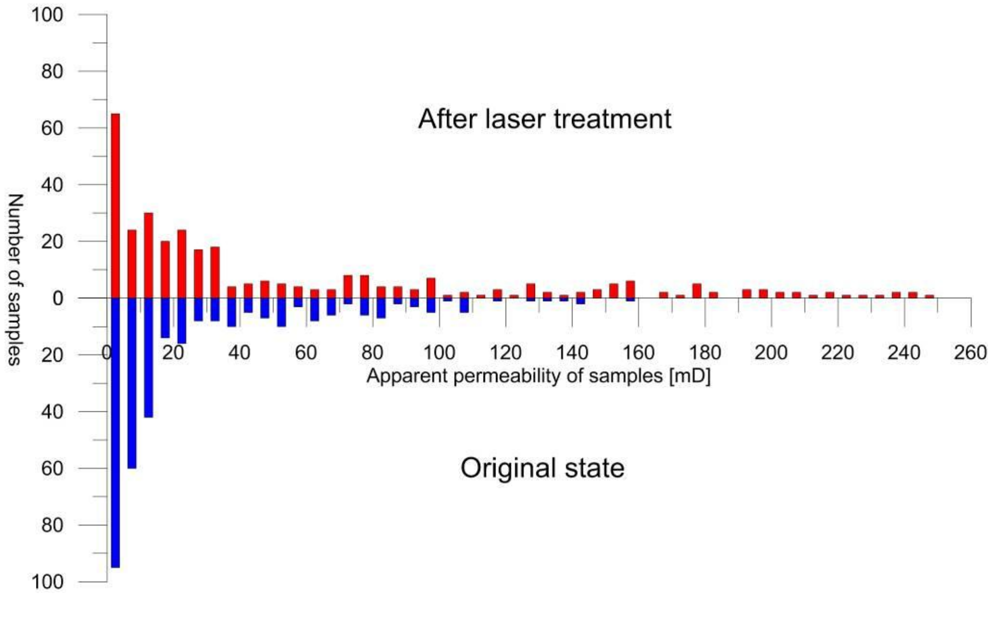

Figure 8. Histogram of apparent permeability of samples before and after the treatment

CONCLUSIONS

A series of permeability tests have been completed in order to determine the effect of laser drillings to the aquifer. Measurements indicated that the laterals drilled using this new technology increases the permeability round the lateral due to heat shock induced fracturing but it also keeps the reservoir integrity. During the tests no sand intrusions or leaking was detected.

The technology may help to complete injection wells in geothermal industry with higher productivity (Szanyi et al. 2011, 2012), to build remedial wells to inject nanoliquids right on the spot or to reach hot spots on highly covered industrial sites. Since the tests showed only small permeability reductions due to laser treatment, we may assume that the melted tube principle may hydraulically work in underground systems.

In hydrocarbon mining well completion laser offers some distinct advantages as easy steering and control. Since the laser head used nitrogen, all fluids are displaced during the drilling process, which prevents the formation from being contaminated by drilling mud.

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