Introduction

Energy provision from the subsurface plays a key role to achieve the climate goals as outlined in the European Green Deal. Given that more than 50% of the energy demand in Europe is based on the (seasonal) requirement for heat, geothermal energy from shallow to mid-depth resources has the potential to deliver a substantial share of this heat demand and contribute to the climate goals. A high degree of uncertainty caused by unknown or limited understanding of the reservoir quality leads to a considerable risk for investors and geothermal operators. The construction of multi-lateral wells is a well-known tool in the oil & gas industry to overcome challenges of reservoir heterogeneity and/or enhance productivity by increasing the reservoir contact, connecting compartmentalised zones and intersecting pre-existing fracture sets. The potential impact of multi-laterals for geothermal sites has been mapped in various studies (i.e., Peters et al., 2018, Lentsch et al., 2020).

The drilling costs for multi-lateral well construction are high when performed with standard rotary steerable systems due to requirements and limitations imposed by the mechanical rotary drilling action. These costs are even higher when the target reservoir section is located in competent (quarzitic) limestones or crystalline rocks where low rate of penetration (ROP) and high drill bit wear are challenges. Until recently, multi-lateral technology has never been considered for geothermal site developments. Recent projects are deploying this technology in sites where the production forecasts are solid and the financial risks are predictable but rely on optimistic cost estimates (Beckers and Johnston, 2022). To tap into the true potential of multi-lateral well construction, the cost per well-meter must be reduced. A cost-effective lateral drilling technology would allow to de-risk geothermal projects with larger uncertainties, enable economic production from lower reservoir quality and ultimately, increase the robustness of geothermal heat provision as investment target.

Canopus' directional steel shot drilling (DSSD) system is a potential game changing technology utilising additional rock erosion by steel particles transported in the drilling fluid and accelerated in the drill bit nozzles (see figure 1a&b). The technology requires minimal weight on the bit (WOB) and uses conventional flow rates and pressures. The additional rock erosion enables high ROPs even in more component rock types while the drilling assembly can be flexible enough to drill ultra short radius laterals. These characteristics are ideal to construct long multi-lateral reservoir drainage structures, even if the reservoir pay zone has limited thickness. Blange et al. (2022) gives a detailed description of the DSSD system functionality and advantages.

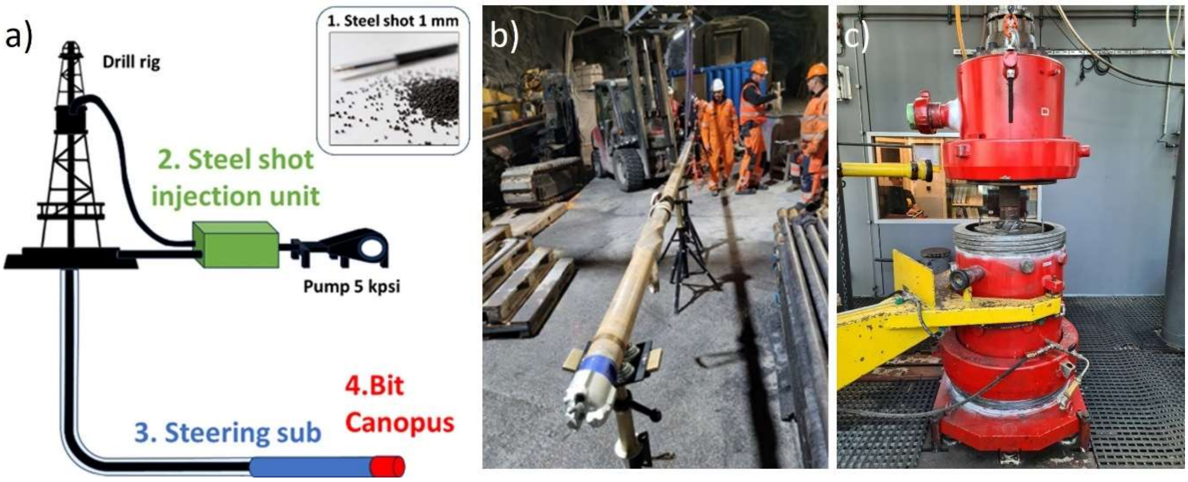

Figure 1 *a) Canopus directional steel shot drilling (DSSD) technology comprising of a steel shot injection system at surface, a hybrid PDC-steel shot drill bit and a down hole steering sub modulating the steel shot concentration for directional control; B) Bottom hole assembly of the DSSD system for the field test in Switzerland, June 2023; c) 50 tonnes drilling simulator at TNO's RCSG lab facility.*

As part of the European GEOTHERMICA project 'DEPLOI the HEAT', the operational performance of Canopus' DSSD system has been investigated. Full-scale lab testing and optimisation at TNO's Rijswijk Centre for Sustainable Geo-Energy (RCSG) and a field test in a mining test facility in Switzerland have been executed within the first year of the development program. Currently, the second series of full-scale lab tests are planned including the final factory acceptance test before the first tool deployment in a live geothermal well is to be executed in 2025.

Comparison of (mechanical) specific energy from full-scale drilling performance testing

To compare the mechanical rock removal by the polycrystalline diamond compact (PDC) cutters of the drilling bit and the erosive action of the accelerated steel shots (SS), a series of drilling test has been performed at RCSG lab with high compressive strength concrete and competent limestones. For this purpose, the classical mechanical specific energy (MSE) analyses (Teale, 1965) is expressed as the mechanical (rotary) power divided by volumetric excavation rate (V_{ex}) (equation 1). The erosive power P_{ss} is expressed as kinetic energy of the steel shots in the carrier fluid (equation 2). Further parameters of equation 1 & 2 can be found in table 1.

$$MSE = (WOB \times ROP + TOB \times \frac{2\pi}{60} RPM)/V_{ex} \qquad \text{Eq.1}$$

$$P_{ss} = (Q \times \Delta P \times C_{ss} \times \frac{\rho ss}{\rho cf}) \qquad \text{Eq.2}$$

The 50 tons drilling simulator at RCSG's lab allows for drilling performance testing at downhole conditions (see figure 1c). Rock samples of 80 x 40 cm can be drilled at elevated hydrostatic pressures to compare the performance of pure PDC bit drilling with combined drilling action of PDC and steel shot (SS) particles. The downhole condition (i.e. hydrostatic pressure) is very important as both the rock removal by the PDC action as well as the erosion by the steel shot particles are much higher at shallow depth than at larger depth. The energy efficiency of PDC drilling reduces over the first few hundred meters of depth due to the so-called cuttings hold-down effect, where the down hole pressure of the drilling fluid pushes down on generated rock cuttings and counteracts their removal. Further, the increased hydrostatic head with depth also suppresses cavitation and cavitation surrounding the jets increases the erosion reach leading to ROP enhancement and unwanted wash-out effects.

Table 1 *Drilling parameters for comparison of mechanical PDC bit drilling with combined PDC and erosive drilling with steel shots. (*increase of TOB and ΔP with addition of steel shots, **in cement)*

Parameter	Symbol	Value	Unit
weight on bit	WOB	10	kN
torque on bit	TOB	300 - 600*	N.m
rate of penetration	ROP	up to 20**	m/hr
rotation per minute	RPM	40	1/min
flow rate	Q	480 - 510	L/min
bit pressure drop	ΔP	200 - 250*	bar
steel shot concentration	C_{ss}	2.1 - 2.6	volume%
density steel shot	ρ_{ss}	7800	kg/m^3
density carrier fluid	ρ_{cf}	1000	kg/m^3

A series of tests were performed with high strength cement, hard Belgian limestone and Swiss limestone relevant for mid-depth geothermal targets in Switzerland. The results of the drilling tests are expressed as specific energy required to remove a volume of rock in MJ/m^3 and plotted in figure 3a. The specific energy unit equals MPa and the unconfined compressive strength (UCS) of the rock type is given for comparison. The UCS is typically between 0.3 and 0.4 times rotary MSE at peak efficiency (Dupriest and Koederitz, 2005).

While the cement sample shows an expected ratio between UCS (grey bar) and MSE (blue bar) in the range of 0.4 (or factor 2.5), the pure PDC action is not optimised for the competent limestones. The

MSE values are considerably higher (factor 5-7) than the UCS values of the rock samples (see figure 2a). Important to note that with the low WOB (10 kN) applied during these tests, a non-optimised state is likely. The situation changes when the steel shot particles are added to the drilling action (red bars). The MSE or specific excavation energy reduces considerably in all three cases by adding additional erosive action to the rock removal process. In hard Belgian limestone, ROP up to 15 m/h is realised and in high strength cement 20 m/h. The erosive power ranges from 26 – 43 kW. This power is taken from the fluid and is delivered by the rig pumps. The additional power consumption is small compared to the total hydraulic power available from the rig pumps ranging from hundreds of kW to some MW.

The better drilling performance is not only a result of the additional erosive drilling action, but the altered bottom hole profile results in a better utilisation of the mechanical rock removal which is reflected in higher torque on bit values, higher bit aggressivity (figure 2b) and larger cutting sizes (figure 2c). Figure 2d illustrated the difference in bottom hole profile from both drilling methods.

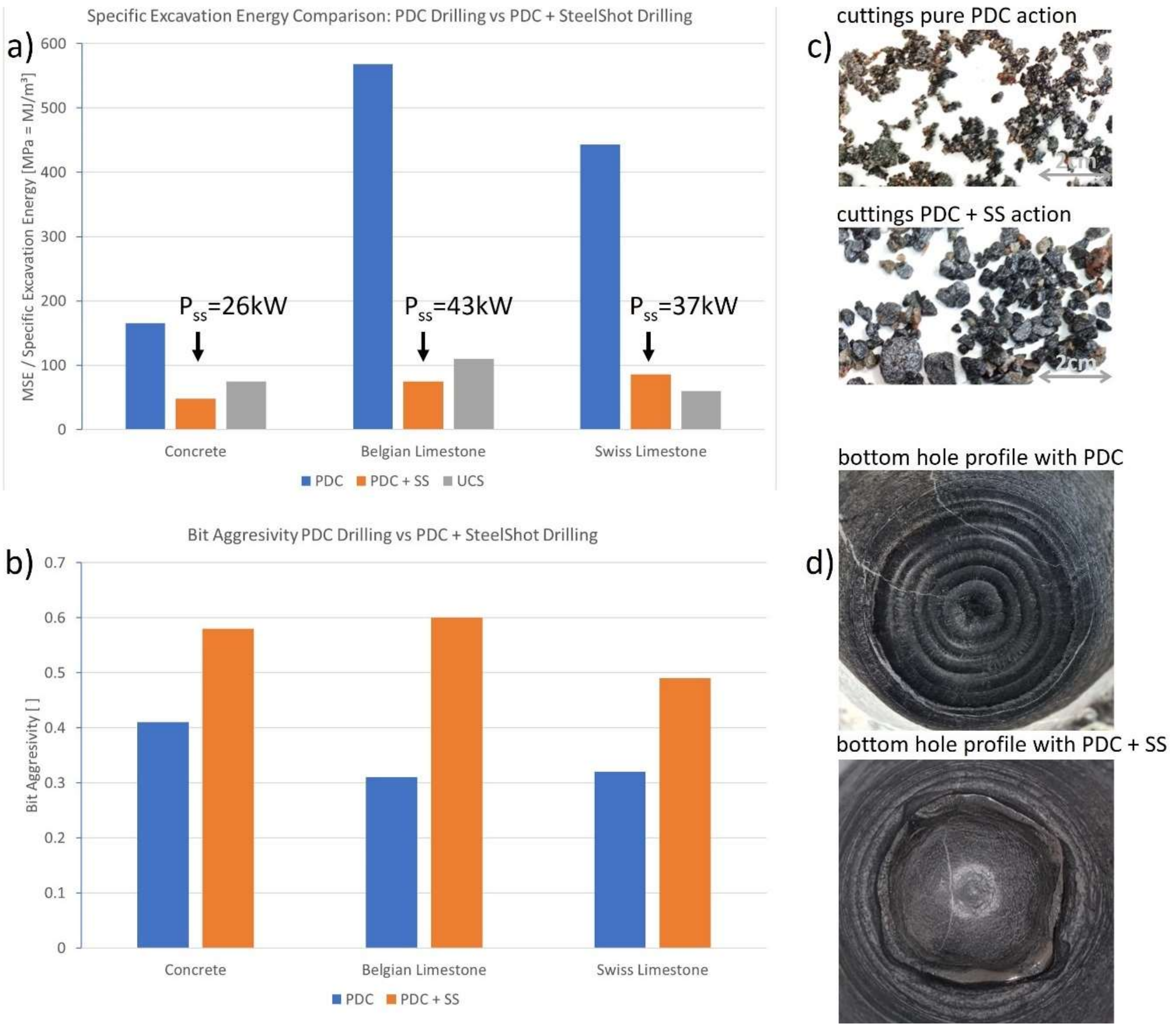

Figure 2 *a) Specific excavation energy comparing mechanical PDC drilling action with additional erosive steel shot (SS) drilling action; b) Effect of the alteration of the hole bottom by steel shots on the PDC bit performance expressed as bit aggressivity; c) Photos of the different cuttings sizes produced; d) Photos of the whole bottom profile illustrating the action of the steel shot loaded fluid jet.*

Specific excavation energy results from the steel shot drilling field trial

During the field test in Switzerland, a mining rig was utilised to drill two sub-horizontal wellbores in a mining test facility with a 4-1/8” drill bit and steering assembly (see figure 1b). Utilising flow rates of 500-550 L/min and particle volume concentrations ranging from 0.1% to 2%, improvements of factor

1.5-3 in ROP and associated reductions of factor 1.5-2 in specific energy (rotary MSE) were observed when steel shots were introduced into the system. The drilling system was limited in the ability to push, thus limiting WOB, and higher heterogeneity in the formations drilled than expected limited MSE and ROP optimisation activities with and without steel shot. A direct comparison of field and lab results is difficult. However, the observed improvements in ROP and reductions in rotary MSE are in line with those observed at RCSG and demonstrate the potential of the system.

Conclusions and outlook

The performance of the directional steel shot drilling (DSSD) technology developed by Canopus has been investigated by means of full-scale lab testing at TNO's RCSG facility as well as during a field test in Switzerland. As important performance parameter for the efficiency of the hole making action, the specific rock excavation energy has been compared for classical, mechanical drilling and combined drilling action utilising a custom-made PDC bit that allows for erosive steel shot drilling.

The lab-based investigation highlighted the increased efficiency in drilling performance expressed in a considerably reduction of specific excavation energy. The higher performance is reflected in higher bit aggressivity leading to larger cutting sizes and higher rate of penetration. Compared to the uniaxial compressive strength, very good drilling performance was achieved in competent Belgian limestone.

The improved drilling has been confirmed during the field test executed in a Swiss mining test facility. The integration of the DSSD system in a drilling operation and the potential to overcome typical limitations (e.g. low ROP) of slim hole laterals drilled by combined PDC and SS drilling action has been demonstrated. The minimum hydrostatic head during the field test imposed challenges due to induced cavitation and wash-outs impacting the ROP and borehole quality. This observation highlights the importance to perform drilling tests with sufficient hydrostatic head as applied during the lab tests at RCSG facility.

Canopus DSSD technology has the potential to enable cost-efficient multi-lateral well construction by improving the drilling efficiency and introducing a new steering principle that allows for tighter radii and longer laterals. This could lead to improved business cases of geothermal projects and therefore help to accelerate the development of a geothermal industry. Within the GEOTHERMICA 'DEPLOI the HEAT' project, the second phase of full-scale lab tests has been kicked off investigating the performance of a DSSD unit constructed for drilling 6" bore holes and the project is to conclude with a pilot of DSSD in a geothermal well in 2025.

Acknowledgements

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