Novel concepts to construct cost effective geothermal wells with Electro Pulse Power Technology

Deep Light

Flow test results and design/operational considerations for mud selection in EPP drilling

D4.2

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Executive Summary

The DEEPLIGHT project aims to develop the Electro Pulse Power (EPP) drilling technology for cost-effective geothermal wells. The novel rock breaking mechanism requires modelling and experimental validation to optimize hole cleaning during EPP drilling operations which was covered by Work Package 4.

The research focuses on understanding the impact of flow rate, pipe rotation, cutting concentration, and rheology on hole cleaning while considering the EPP specific particle size distribution as created by the EPP rock breaking mechanism. Experiments are conducted at the Rijswijk Centre for Sustainable Geo-Energy to validate and calibrate a physics-based semi-empirical model. The study aims to identify the minimum threshold combination of these factors to initiate effective hole cleaning across different inclinations.

Key findings indicate that pipe rotation significantly enhances cuttings transport, especially for coarser particles. Inclination effects are size-dependent, with finer solids showing better performance under inclined conditions. Higher-viscosity drilling fluids generally improve hole cleaning efficiency, particularly for larger cuttings. The study also highlights the importance of controlled drilling rates to maintain stable transport and minimize the hydraulics power required to clean the hole.

Additionally, a Computational Fluid Dynamics (CFD) study was conducted to improve the hydraulic design of the EPP electrode. The study revealed that adding viscosity to the drilling fluid and using rotation significantly enhance hole cleaning around the electrodes. The findings suggest that future work should focus on optimizing electrode configurations.

Overall, WP4 of the DEEPLIGHT project demonstrates that the integrated approach combining experimental data, modelling, and CFD analysis provides a robust framework for optimizing drilling operations and enhancing hole cleaning performance.

To conclude, viscous drilling fluids and rotation are essential elements in the EPP tool design and operational planning.

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1 Introduction

The research approach to identify hole cleaning requirements for a novel EPP drilling technology is two-fold: modelling and experimental validation. Initially, a physics-based semi-empirical model has been prepared as described in DEEPLIGHT deliverable D4.1 (Blinovs, Battistutta, & Van Og, 2025)[1]. Subsequently, experiments has been conducted on the cutting flow loop at Rijswijk Centre for Sustainable Geo-Energy (RCSG) to generate relevant data, which will be used to validate and optimize the model. This work has been presented and at the European Geothermal Congress 2025 in Zurich (Battistutta, et al., 2025).

The study aimed to identify the impact of flow rate, pipe rotation, cutting concentration and rheology on hole cleaning, and to identify a minimum threshold combination at which minimum hole cleaning will be initiated across two different inclinations. Further, the experimental study served to characterize cuttings transportation regimes under varying velocity conditions. Lastly, transient response of the system to changes in pipe rotation and flow rate will be identified. Qualitative observations from the experimental results will be used to develop a quantitative hole cleaning model tailored for EPP drilling conditions.

1.1 Abbreviations

Abbreviation	Description	Comment
BHA	Bottom Hole Assembly	
CFD	Computational Fluid Dynamics	
DAQ	Data acquisition system	
DPM	Discrete phase model	
dP	Delta P (pressure drop)	
EPP	Electric Pulsed Power	
Hz	Hertz (1/sec)	
PDC	Polycrystalline Diamond Compact	
PLC	Programmable logic controller	
PSD	Particle size distribution	
ROP	Rate of Penetration	
RPM	(Pipe) Revolutions per Minute	
YP	Yield point	

[1] https://deeplight-project.eu/downloads/

2 Flow Loop

2.1 Experimental Setup

The experiments were conducted at TNO's Rijswijk Centre for Sustainable Geo-Energy, using a specialized cuttings flow loop setup, see Figure 1. It is designed to investigate the formation and dispersion of cuttings beds, as well as other phenomena associated with cuttings transport in a simulated borehole environment.

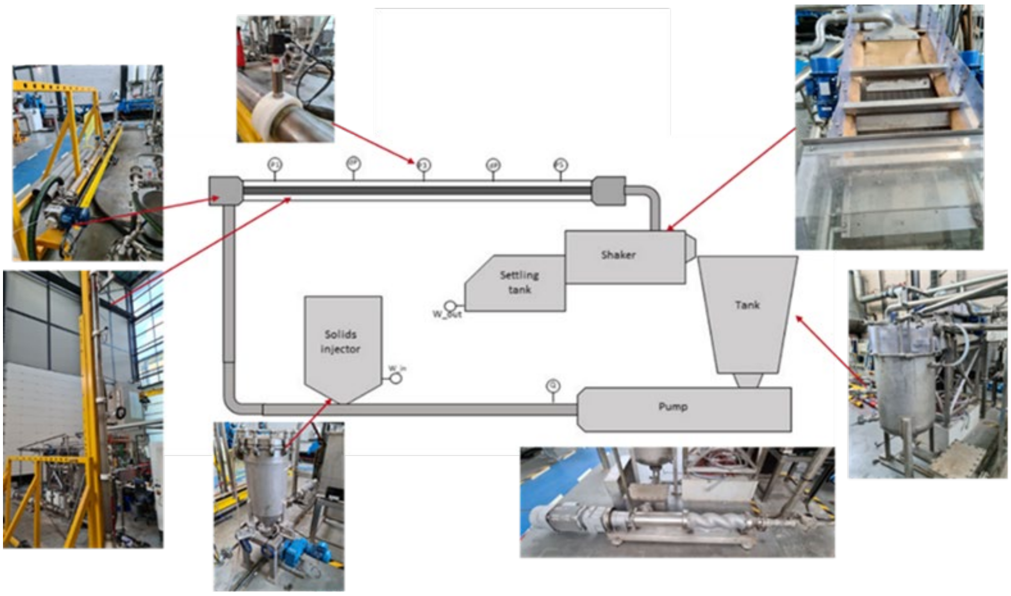

Figure 1. Cuttings flow loop at TNO's Rijswijk Centre for Sustainable Geo-Energy used for experiments .

The flow loop was designed to accommodate a range of testing inclinations, varying from 0° to 180°. It includes a shaker integrated into the flow loop to separate solids from the fluid prior to recirculation. The setup is equipped with multiple pressure sensors, a flow meter, and a programmable logic controller (PLC) for regulating cuttings injection rates, the rotational speed of the inner pipe, and the pump flow rate. All sensors and the PLC are connected to a data acquisition system (DAQ). Data in experiments were recorded in real time at a sampling frequency of 10 Hz. In addition to the DAQ system, experiments were video recorded using a camera.

The transport flow setup is observed and measured along the pipe section, which consists of an inner rotary pipe that emulates the drilling bit and an external transparent polycarbonate pipe, both with a length of 6 m, as illustrated in Figure 2.

PIPE	mm
outer pipe OD	100
outer pipe ID	90
Annular space	20
Inner pipe OD	50

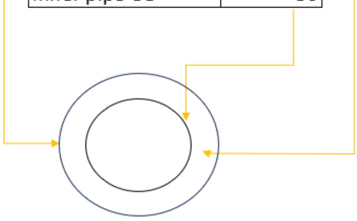

Figure 2. Diameter measurements of the pipes

The annular space imposes a limitation on the size of the cuttings particles, as their diameter cannot exceed one-third of the annular space. This was in line with the maximum expected size of EPP cuttings based on the particle size distribution analysis, as explained further in the paper.

2.2 Sample preparation

A small sample of cuttings (Figure 3) from a short drilling test with EPP technology in concrete was obtained from the Technical University of Dresden, partner in the Deeplight consortium.

Figure 3. The main frame shows a real sample created by EPP electrodes. The smaller frame on the top right displays a microscope image of the sample within 1.4 and 2 mm size; cuttings from EPP drilling test provided by TU Dresden.

The sample was used to replicate artificial cuttings by analyzing the size and shape of cuttings produced by drilling with EPP technology. The sample included larger cuttings than typically expected from continuous drilling operations, as such cuttings would be regrinded during continuous drilling and further broken down due to rotational and hydraulic forces during upward flow towards the surface. These larger cuttings were still considered within the fourth sample batch.

The cuttings were dried at 110 °C to remove moisture and then sieved using mesh sizes ranging from 0.05 mm to 16 mm. Each fraction was weighed to determine the particle size distribution (PSD), using a Retsch AS 200 control shaker set at an amplitude of 1.0 for five minutes per column. The weight loss due to this removal was 0.1%, which is within the margin of measurement error. Microscopic analysis indicated that the particles were predominantly subangular to subrounded (Figure 3). The resulting Particle Size Distribution (PSD) enabled the design of synthetic samples for flow loop experiments (Figure 4). The analysis identified three main grain size ranges, which guided the selection of three pre-sorted commercial sands to replicate the original sample composition. These sands, with grain sizes of 0.1–0.5 mm, 0.4–0.8 mm, 0.71–1.25 mm, and 1.2–2.5 mm, were obtained from a sand supplier in The Netherlands.

Based on these materials and the PSD data, four artificial batches of 150 kg each were prepared to match the limited volume of the cuttings injection vessel used in the flow loop experiments. Batches 01, 02, and 03 each consisted of sand within a specific grain size range: 0.1–0.5 mm, 0.71–1.25 mm, and 1.2–2.5 mm, respectively. Batch 04 was designed to closely replicate the original sample and included a mix of the three sand types, supplemented with pebbles in the 2–4 mm and 8–16 mm ranges. According to supplier specifications, both sands and pebbles followed a normal distribution. To define the composition of batch 4, each fraction from the original PSD was matched with predefined size categories: 0.1–0.5 mm, 0.4–0.8 mm, 0.71–1.25 mm, 1.2–2.5 mm, 2–5 mm, and 8–16 mm. The individual components were then weighed and manually blended to produce artificial samples suitable for the experiments.

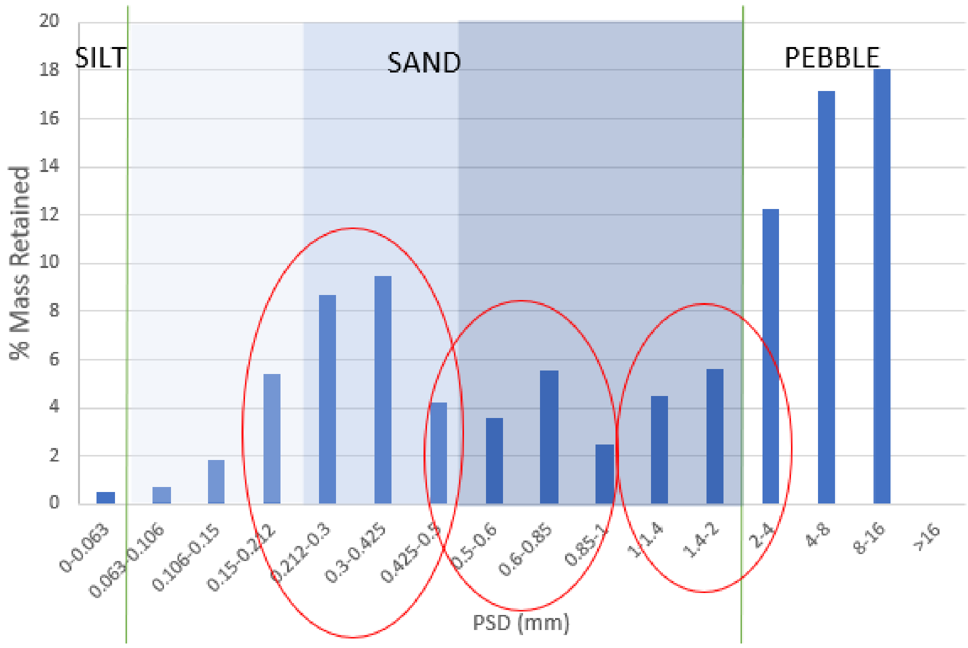

Figure 4. Particle Size Distribution analysis of the sample. The plot displays the mass retained during the sieving process, with the X-axis representing grain size ranges and the Y-axis showing the retained mass as a percentage of the total sample.

2.3 Rheology

The electric conductivity and permittivity of the drilling fluid may affect the EPP rock-breaking mechanism therefore two fluids in experiments were used: water (WBM1) and viscous water (WBM2, YP ~3 lb/100 ft²). Viscosity was adjusted using Xanthan Gum (Imtiaz et al, 2021) and measured with a Fann 35SA Viscometer (Figure 5). Water served as a baseline whereas the viscous fluid aimed to replicate geothermal drilling fluids, typically in range of YP 10–30 lb/100 ft². Due to shaker restriction, a YP of 3 lb/100ft² was the highest viscosity that could still pass through the mesh. This value was still sufficient to showcase the impact of rheology on the minimum hole cleaning requirements.

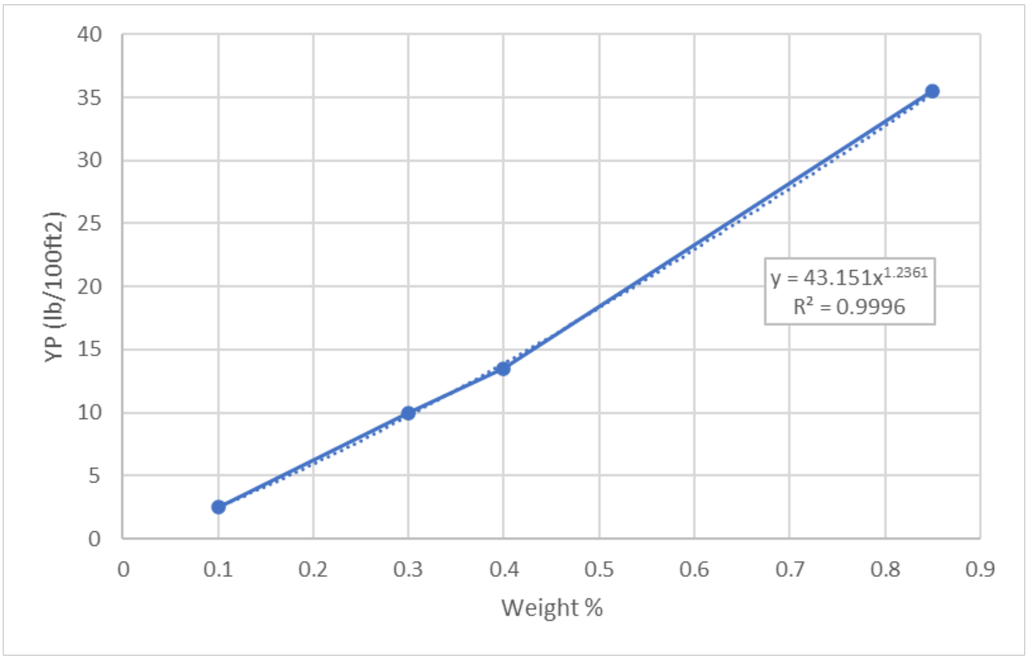

Figure 5. Experimentally measured yield point of muds obtained by adding Xanthan Gum to water at room temperature.

2.4 Test execution

The primary objective of this series of experiments was to train the physics-based model that describes the transport behavior of cuttings carried by drilling fluid within the annular channel surrounding the drill pipe. The cuttings behavior was analyzed and recorded as a function of flow rate, drill pipe rotation, drilling fluid rheology, cuttings concentration, and pipe inclination angle.

To acquire data based on a complete set of the operational parameters, a test matrix was developed. The experimental phase consists of 20 runs to assess the impact of various operational parameters on the wellbore transport of cuttings, as outlined in Table 1. Each test consisted of a series of steps, during which only one parameter was changed at a time to isolate its effect on pressure drop (dP), which was used as the indication of cuttings bed buildup (e.g. sudden increase in dP). For each cuttings concentration, the flow rate varied from 90 to 300 L/min, in consistent step increments. Even though flow rate was used as a reference in experiments, the superficial velocity of cuttings is what ultimately matters for the field operation. At each flow rate, the pipe rotation was varied between 0, 60 and 120 RPM. Cuttings injection rates were around 2, 4 and 6 kg/min, latter being the maximum value due to setup restrictions. The sequence of flow rate and pipe rotation variation was repeated for each cuttings injection rate. Figure 5 represents a part of one test where flow and pipe rotation were varied at constant cuttings injection rate of 5 kg/min. This sequence of steps was repeated for each of the four cuttings batches, two drilling fluid rheologies (water WBM1 and viscous water WBM2), and at two pipe inclination angles: 0° and 60°. This resulted in a total of 16 different tests, with 20 steps per test run. The total volume of cuttings available per test was approximately 150kg due to the limitation in the cuttings storage tank capacity.

Table 1. Test matrix.

			Constants		Variables		
Run	**Remark**	**Inclination**	**Mud Type**	**Cuttings type**	**Cuttings v%**	**Flow rate**	**Pipe RPM**
1		0	WBM1	Batch 1	0.5-1.5	200-500	0
2		0	WBM1	Batch 2	0.5-1.5	200-500	0
3		0	WBM1	Batch 3	0.5-1.5	200-500	0
4		0	WBM1	Batch 4	0.5-1.5	200-500	0
5		0	WBM2	Batch 1	0.5-1.5	200-500	0
6		0	WBM2	Batch 2	0.5-1.5	200-500	0
7		0	WBM2	Batch 3	0.5-1.5	200-500	0
8		0	WBM2	Batch 4	0.5-1.5	200-500	0
9		60	WBM1	Batch 1	0.5-1.5	200-500	0-60-120
10		60	WBM1	Batch 2	0.5-1.5	200-500	0-60-120
11		60	WBM1	Batch 3	0.5-1.5	200-500	0-60-120
12		60	WBM1	Batch 4	0.5-1.5	200-500	0-60-120
13		60	WBM2	Batch 1	0.5-1.5	200-500	0-60-120
14		60	WBM2	Batch 2	0.5-1.5	200-500	0-60-120
15		60	WBM2	Batch 3	0.5-1.5	200-500	0-60-120
16		60	WBM2	Batch 4	0.5-1.5	200-500	0-60-120
17	Optional	0-60	WBM1-2	Batch 1-4	0.5-1.5	200-500	0-120
18	Optional	0-60	WBM1-2	Batch 1-4	0.5-1.5	200-500	0-120
19	Optional	0-60	WBM1-2	Batch 1-4	0.5-1.5	200-500	0-120
20	Optional	0-60	WBM1-2	Batch 1-4	0.5-1.5	200-500	0-120

3 Data interpretation and discussion

The comprehensive dataset from the experimental runs — covering variations in cuttings type, drilling fluid rheology, pipe rotation, inclination, and cuttings feed rate — offers detailed insights into the governing mechanisms of hole-cleaning performance within the given framework. This approach extends conventional evaluation methods by incorporating rigorous data filtering, multivariate optimization, and advanced trend diagnostics to improve the reliability of performance interpretation.

Hole-cleaning performance again demonstrates clear, coupled dependencies on pipe rotation, inclination, mud type, particle size, and feed rate (ROP). Increasing pipe rotation continues to enhance cuttings transport, reflected by consistently lower ΔP values across all batches. The rotation effect, while moderate for fine and medium cutting size (Batches 1–2), becomes increasingly pronounced for coarser cuttings (Batches 3–4), where mean ΔP reductions of over 1 mbar/m confirm rotation as the dominant control on bed erosion and slip velocity recovery.

Inclination effects remain size-dependent. At 60°, hole cleaning efficiency declines for Batches 2–3, where ΔP rises notably (e.g., Batch 3: 8.64 → 11.62 mbar/m). Conversely, fine and mixed batches (Batches 1 and 4) show little to no hole cleaning deterioration under inclination, suggesting that finer solids and higher fluid viscosity help counteract the gravitational bias on the low side. These results highlight the transition between suspension-dominated and bed-dominated transport regimes.

Drilling fluid rheology exerts a consistent influence on system behavior. The higher-viscosity formulation (WBM 2) generally outperforms WBM 1, yielding lower ΔP and greater flow stability in Batches 1, 3, and 4. The inverse trend observed in Batch 2, where WBM1 produces a slightly lower mean ΔP, points to a complex interaction between viscosity and intermediate particle size. The substantial improvement with WBM 2 for coarse solids (up to 5 mbar/m ΔP reduction in Batch 3) reinforces the critical role of viscous drag in stabilizing bed motion and enhancing cuttings suspension.

Cutting feed rate, i.e. drilling rate, remains a primary determinant of cleaning performance. Increasing the cuttings feed from 1.9 to 5.7 kg/min significantly elevates ΔP in most cases—particularly in Batches 1, 3, and 4—reflecting the expected pressure buildup from higher solids loading. The pronounced sensitivity of Batch 3 further identifies it as the operational limiting case for sustained transport efficiency.

Overall, the findings demonstrate that pipe rotation provides the most consistent improvement in hole-cleaning performance across all operational conditions, particularly under inclined geometries and coarse-particle loading. Complementary effects from fluid rheology and controlled feed rates further enhance system stability and transport effectiveness, ensuring robust and efficient hole-cleaning performance across a wide range of drilling scenarios. A visualization of the data and the effects can be seen in Figure 6.

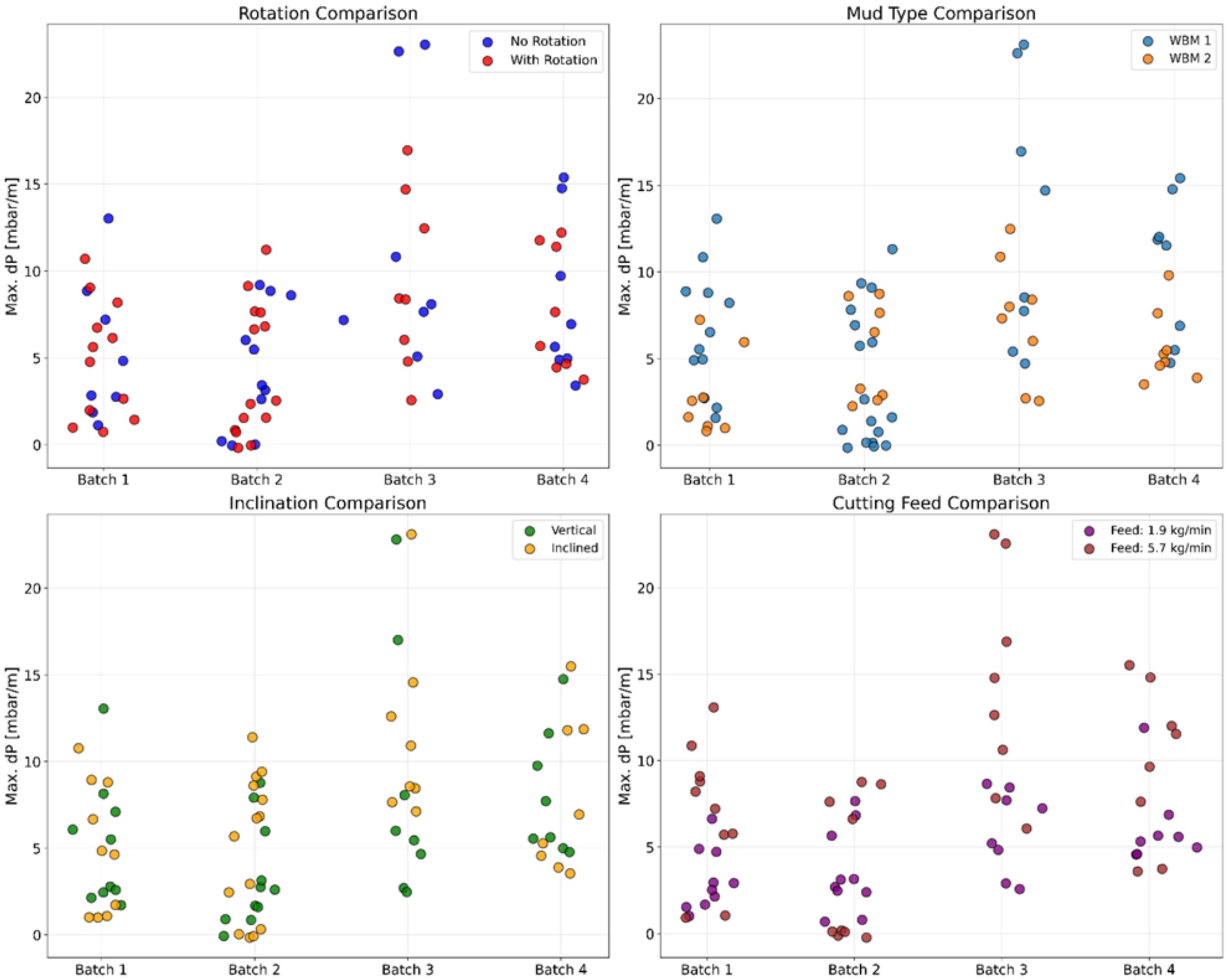

Figure 6. Effect of operational parameters on maximum pressure drop (ΔP) across Batches 1–4. Rotation and higher-viscosity mud (WBM 2) reduce ΔP, particularly for coarser solids (Batches 3–4). Inclination and higher feed rates increase ΔP, indicating reduced hole cleaning efficiency. Overall, pipe rotation remains the most effective measure for maintaining stable transport.

4 Cutting removal around electrodes

The hydraulics and hole cleaning design of the electrode bit is essential to get good penetration rates. The hole cleaning model will not be able to gain insight on the flow and cutting behaviour around the electrodes as it concerns a very local and well-defined area. However, this is where CFD is very suited and therefore WEP supported a Bachelor student of the Hanze Hogeschool to perform a CFD study (Melie & Van Og, 2025) which is summarized in this chapter. The study aimed to improve the electrode design and to gain inside on the impact of the various parameters such as rotation and flow rate. The EPP drilling electrode design lacks optimum hydraulic parameters for effective drilling cuttings removal by the drilling fluid, which may result in cutting rework, a loss of operating efficiency, and tool damage. In addition, despite conventional drilling, in theory, the electrode could function without rotation, which may harm the removal of drilling cuttings. Therefore, the effect of rotation has also been modelled.

4.1 Methodology

ANSYS-FLUENT, the student version, is used to predict the hydraulic performance of the EPP electrode and flow field simulation around it. Mesh generation is one of the most essential steps in the numerical solution of partial differential equations in physical CFD analysis. A mesh discretizes a geometric domain into small shapes, such as triangles or quadrilaterals (2D) and tetrahedra or hexahedra (3D). Since the geometry of the electrode is complex, containing electrodes, internal channels, cone nozzles, and fluid volume around the bit, this process requires generating a fine and qualitative mesh.

The type of solver used is pressure-based, with an absolute velocity formulation, and a steady time. The reasoning behind this choice is that the drilling simulations need to focus on velocity and pressure, since these two parameters are important in the hole cleaning process. The density-based solver is used only when heat transfer is essential, and the density is variable. The steady time modelling assumes that the fluid properties and flow conditions do not change over time, so the system is reaching a state where all variables remain constant, and any transient effects are ignored.

For particle tracking simulations, there are two more models that can be utilized: the discrete phase model (DPM) and the multiphase model. Analysing both models and comparing them also with study cases on PDC bits, it is clear that the DPM is more utilized in the drilling industry, especially around the bit, because the volume fraction of particles which remains in the fluid domain needs to be small for an efficient removal, and since it is essential to see how each particle react due to their different dimensions and mass fractions.

4.2 Modelling & Engineering

In ANSYS FLUENT, a geometry can be created within the software or imported from another CAD software via a STEP file. Since the step file of the complete tool was too complex, the design had to be simplified as much as possible, as seen in Figure 7.

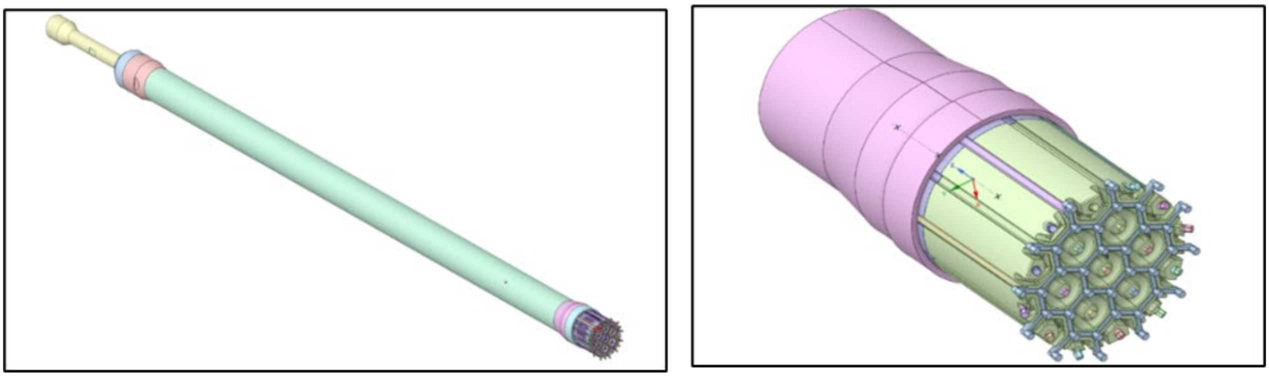

Figure 7. Left: Complete EPP tool; right: Simplified Electrode design.

The simplified electrode's initial design represents a geometrical model with a 12.25-inch (311.15 mm) diameter displaying positive and negative electrodes generating pulsed plasma to break the rock.

Since these simulations are based on a computational fluid dynamics process, a fluid domain needs to be established. It is crucial to have different boundaries because during the CFD post processing, the behaviour of the fluid or particles can be visualized on each boundary selected individually, see Figure 8. The inlet and the outlet are represented by the colours blue and red, respectively.

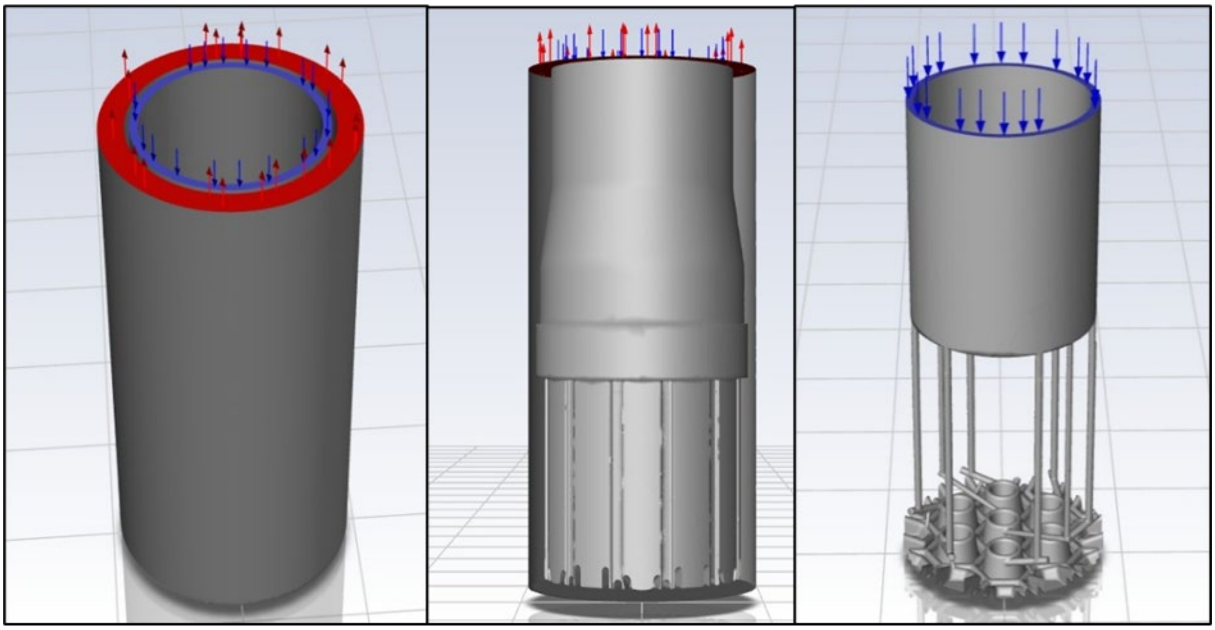

Figure 8. a. Fluid domain around the bit; b. Fluid domain near electrode walls & borehole; c. Fluid domain hydraulic design

The mesh generation for the electrode is a challenge since it needs to meet both a small number of elements and decent quality. The first decision made was to generate the mesh only on the fluid domain, since this project is considering the behaviour of the drilling fluid used, and later the drilled cuttings transportation by the fluid, see Figure 9.

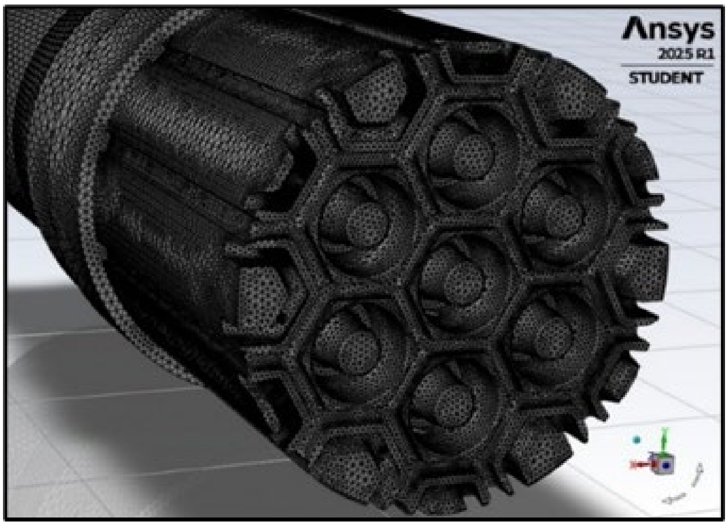

Figure 9. Mesh around electrodes.

The particle injection occurs at the bottom hole wall, where the electrodes break the rock. This injection type is surface injection and injects particles from a chosen surface, according to the set number of streams. There are more considerations to be discussed about the particle injection, such as the type of particles, the material of the particles, the diameter distribution with its point properties, and the physical models.

4.3 CFD results

The flow velocity and flow paths around the electrodes will determine the effectiveness of removing cuttings. Figure 10 shows the flow velocities around the electrodes and velocities are low and don't a clear direction towards the annulus from where the cuttings will be transported upwards. Modelling pressures and flow velocities were used to optimise the internal flow paths of the bit to bring them closer to acceptable levels.

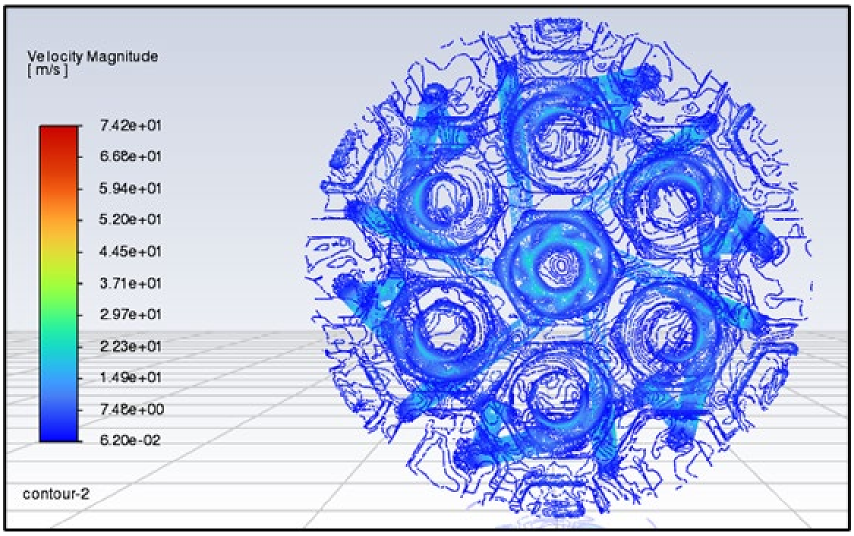

Figure 10. Flow velocity around electrodes. No clear flow path outwards to the annulus is visible.

ANSYS FLUENT calculates the residence time using the maximum number of time steps and the resulting volume fractions to see where the particles are accumulating.

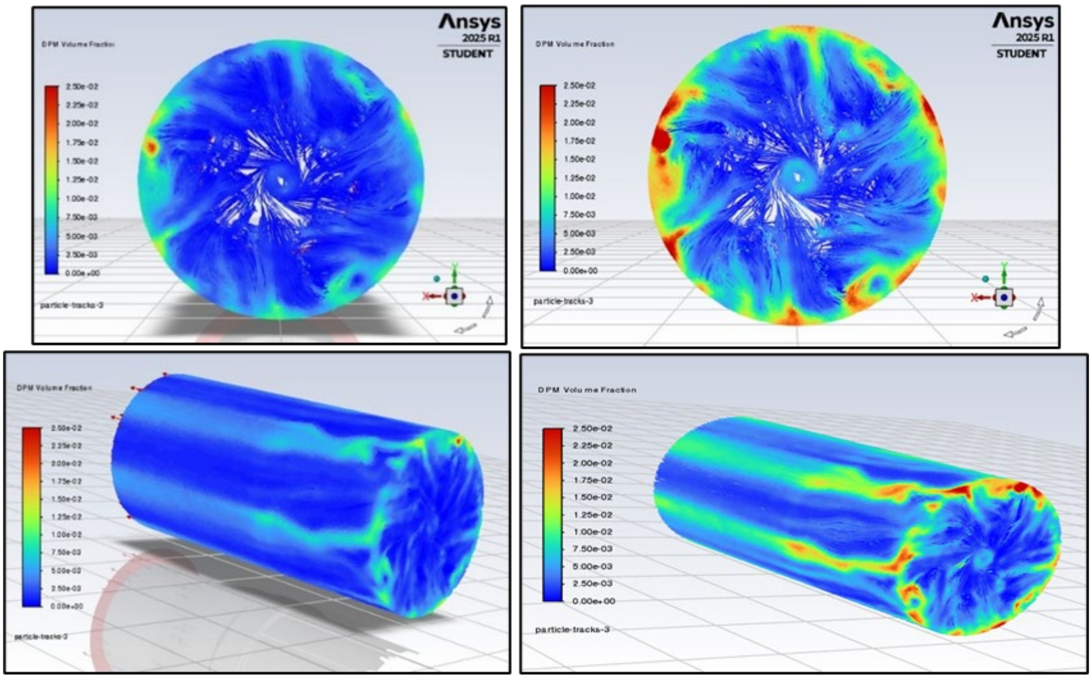

Figure 11.a. Particle Volume fraction bottomhole ROP 5m/h; b. Particle Volume fraction bottomhole ROP 10 m/h; c. Particle volume fraction annulus ROP 5 m/h; d. Particle volume fraction annulus ROP 10 m/h

Figure 11 shows that with increasing ROP more particles seem to accumulate at the outside of the electrodes. The particles also seem to struggle to cross the annular area with the smaller EPP body. Furthermore, clear lines parallel to the flow in which particles accumulate are visible.

Figure 12 shows the volume fraction for the case of adding rotation and viscosity at 20 m/hr. A more uniform distribution is visible. Due to these improvements, the drilling efficiency has increased from 44.0% to 50.5%, considering the escape mass at the outlet. This is an almost 15% improvement.

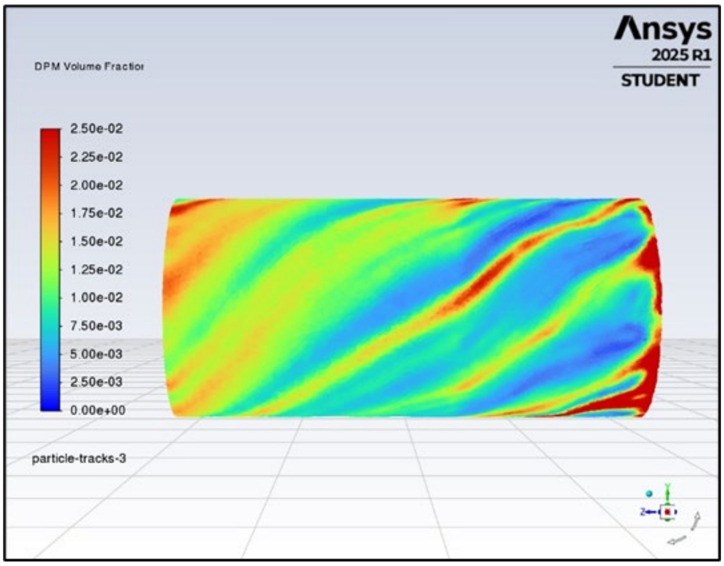

Figure 12. Particle volume fraction at 20m/hr with voscosity and rotation.

4.4 Recommendations

After completing all phases of the project and based on the final results it can be concluded that CFD analysis is an effective technique to understand the hydraulics around the EPP bit and to identify opportunities to improve cutting removal and increase drilling rates. The CFD studies showed critical points in the hydraulic design that will negatively impact the cuttings removal around the electrode. The key lessons-learned are:

- Initial designs had very high flow rates inside the internal channels which could erode the bit from the inside. CFD helped to lower the flowrates and also he pressure drop significantly.
- Due to the improved pressure drop and the addition of more flow to the middle electrode, the flow is spread below the electrode better than in the first design, helping in the hole cleaning process.
- In the particle transportation simulations, it has been observed that at high penetration rates, particles settle more on the bottom hole and in areas where the annular region is the smallest. Also, at 20 m/h ROP, the particles are reflected into the cones, creating bed formation between electrodes. The particles settle more on the electrode's wall side than on the borehole walls, also due to the absence of a defined junk slot area. However, the implementation of only 10 rpm rotation and a viscosity enhancement of 0.1 wt% XT, solved the issue with the particles which accumulates in the annular area.
- The efficiency of cutting transportation shows the use of water and stationary applications, with fluid rheology being one of the most critical aspects of hole cleaning. For the small addition of rotation and viscosity, the efficiency improved with 15%.
- The bit is currently not designed or optimised for rotation. A rotational optimised design will require significantly less electrodes and will create space for internal and external flow channels and potentially added structural support.
- To improve cutting removal, well-defined flow paths which are hydraulically connected to the junk slot area are needed.
- Also, using water during drilling is not ideal, since the rheological effect is essential, a percentage of xanthan gum must be added to the base fluid.
- Not to mention, even if the particles can be removed to some extent in theory, and the range of particle sizes is between 0.15 and 16 mm, the distance between a plus and minus electrode is 30 mm, which will lead to the risk of creating cuttings that will get stuck, while the smallest annular distance is 22 mm.

5 Conclusion

This integrated analysis highlights the complex interplay between operational variables and hole-cleaning efficiency in (EPP) drilling environments. Sixteen lab experiments were performed, varying hole angles, pipe rotation, particle injection rate, flow rate, particle size, and fluid rheology. They are reported in detail in a separate deliverable report D4.1 (Blinovs et al., 2025). Based on these observations, four distinct bed types were identified: dunning, stationary bed, dynamic bed, and free homogeneous flow.

Among the investigated factors, pipe rotation emerged as the most consistently beneficial intervention, significantly lowering both power consumption and flow rate requirements related to hole cleaning. Inclined wellbore trajectories imposed substantial hydraulic burdens, particularly when combined with larger or more cohesive cuttings, as expected in EPP drilling. The superior performance of drilling fluid WBM 2 over WBM 1 underscores the importance of fluid selection in supporting stable suspension under shear, even though the EPP rock-breaking mechanism may limit drilling fluid options. Additionally, increasing cuttings feed rates, or increased drilling rates, exacerbates hydraulic resistance unless compensated by adequate flow rate, a behaviour that can be quantified through differential pressure analysis. Slip velocity and differential pressure trends were shown to provide reliable indicators of hole-cleaning performance.

The physics-based model developed in this study achieved 75.3% accuracy across experimental conditions, demonstrating that hole-cleaning sufficiency can be identified using standard drilling operation measurements. The model can be further improved by (1) incorporating additional experimental data to enhance parameter robustness, (2) developing fluid-specific parameter sets for different mud types, and (3) implementing adaptive parameter adjustment based on real-time operational feedback.

Cutting removal around the electrodes is essential to prevent regrinding and to achieve a sustainable drilling progress. A CFD study on cutting removal around the electrodes showed that adding viscosity to the drilling fluid and to use rotation had a clear positive hole cleaning effect. The study also showed that the investigated EPP electrode design didn't consider cutting removal, hydraulics and rotation.

Future work should focus on expanding the experimental database and integrating machine learning approaches to improve parameter prediction accuracy. Collectively, these findings reinforce the importance of coordinated optimization across mechanical, fluid, and hydraulic domains to ensure reliable and energy-efficient hole cleaning, with the enhanced modelling framework providing a solid foundation for operational decision-making and EPP compatible drilling fluid optimization. Improved electrode configurations are needed and should be designed using CFD.

To conclude, viscous drilling fluids and rotation are essential elements in the EPP tool design and operational planning.

6 References

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