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Hydraulic Drilling Nozzle Design and Research

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Abstract: In light of the European Union's zero-emissions policy and the growing demand for energy associated with technological advances, it is necessary to consider adopting technologies and innovative solutions that simultaneously reduce greenhouse gas emissions while increasing potential extraction from existing hydrocarbon deposits, for example. This can result in increased production from deposits with low reservoir energy values or those in which the energy value does not allow the resource to be exploited on its own. By using a hydraulic drilling nozzle that harnesses the hydraulic energy of the fluid stream for workover, the possibility of increasing the contact between the reservoir layer and the producing well increases in direct proportion to the number of small-diameter radial wells drilled with a hydraulic rotary head from a horizontal well toward the reservoir layer. The main aspect of this paper is to outline an algorithm for the design of rotary drilling heads to maximize the use of the hydraulic energy from fluid streams flowing from the face of innovative drilling tools. The presented design algorithm allows changing the mutual position between the holes in the face section and the angle of the holes with respect to the longitudinal axis of the designed hydraulic rotary nozzle, simplifying the design work. The use of the rotary head developed using this algorithm enables seamless drilling in rocks with compressive strength R_c = 50 MPa, considering the drilling progress at ROP = 4 mm/s.

Keywords: hydraulic radial drilling; drilling nozzle; nozzle designs; radial jet drilling; small diameter borehole; hydraulic energy

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1. Hydraulic Radial Jet Drilling System

At present, jet nozzle drilling technology is widely utilized for cutting, hydraulic jet drilling, or pipeline cleaning due to its effective energy concentration in the jet. The general equipment and tool arrangement for creating radial holes using a high-energy liquid jet flowing through the openings of the nozzle at high pressure includes some necessary pieces such as a coiled tubing unit, a casing windows milling kit, positioning kit, high-pressure elastic hose, deflector, anchors, packers, and at the end of the high-pressure hose, an installed hydraulic drilling nozzle with openings on its tool face (Figure 1) [1–3], (Figure 2) [4]. This approach is commonly found in various configurations and is extensively documented in numerous publications and patents [5–10]. While specific solutions may differ in technical specifics, the basic method for drilling radial boreholes remains grounded in hydraulic jet drilling techniques. Most equipment for drilling lateral boreholes from a parent well requires the creation of a hole in the casing wall using a tool head, typically in the form of a mill. Before drilling into the rock formation, it's often necessary to mill through the casing and cement sheath. This is done using either a tungsten carbide mill (which needs to be retrieved to the surface) or a jet nozzle (like the mill), which is used to bore through the rock. The drive for the milling head/mill is provided by a motor suspended on coiled tubing (CT) wound on a drum. A downhole hydraulic or electric motor may require a gearbox to achieve the appropriate rotational speed for the milling bit cutting through the casing wall. The motor needs to be anchored in the production or casing tubing to transfer the resistance torque from the mill. Then, to pass through the hole in the casing, a hose with a jetting head is used to erode a lateral hole in the rock formation. As the drilling progresses, the coiled tubing is usually lowered, to which the flexible hose is attached. The differences generally lie in the method of creating holes in the casing. For each subsequent lateral borehole, the milling head, drive assembly, and coiled tubing must either be retrieved from the deflector and replaced with a drilling tool, such as a jetting nozzle, or the jetting head bores through the casing, continuing to drill the hole to a specified length.

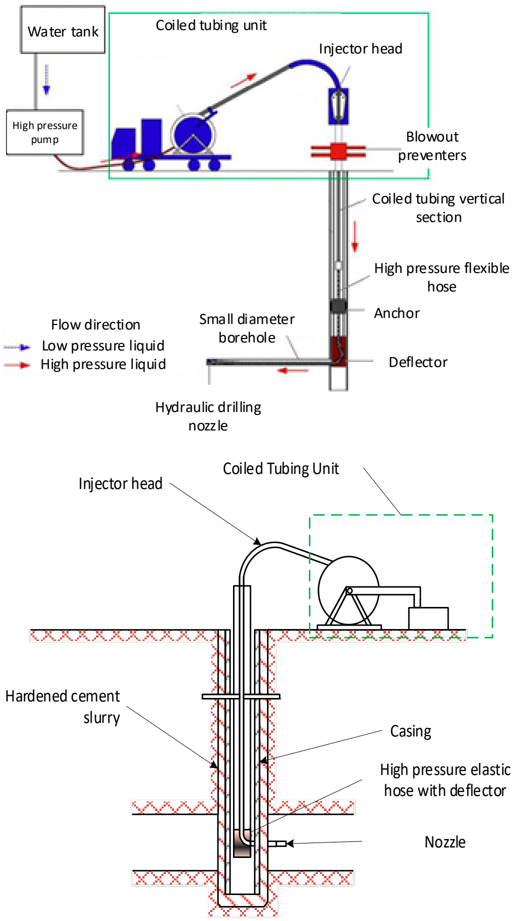

Figure 1. Ultrashort radius radial system (URRS) scheme [1,2].

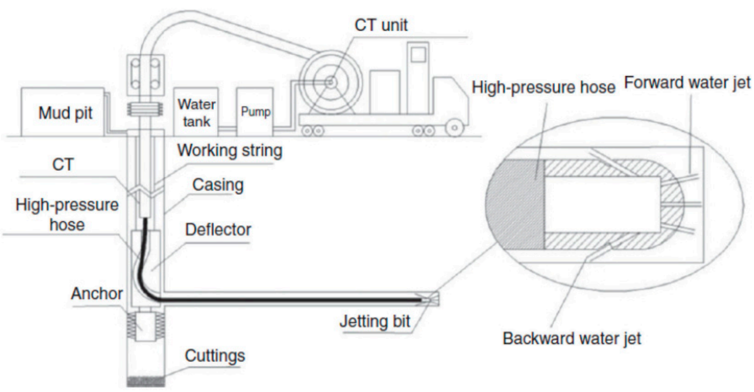

Figure 2. Ultrashort radius radial system (URRS) scheme with indication of hydraulic nozzle [4].

During the drilling of such radial boreholes, the sections are typically horizontal, varying in length from 100 to 300 m, with the diameters ranging between 20 and 60 mm. The significant variability in horizontal section lengths is due to specific requirements for the length of the drainage zone. The absence of a fixed borehole diameter results from the nature of nozzle hydroprobing, the structure of the wellbore medium, and various technological factors and parameters associated with the reservoir rock.

In radial drilling systems, achieving the desired objective is crucial: to create a horizontal borehole with a diameter ranging from 20 to 60 mm and a length of up to 200 m using hydroabrasion techniques in rocks of specified strength, porosity, and permeability, containing specific reservoir fluids, and located at a certain depth. When considering the entire system from the beginning, which includes the Coiled Tubing Unit with the tubing wound on the drum and the working fluid tanks, parameters such as the tensile strength of the flexible tubing, the density and viscosity of the working fluid, the resistance between the flexible tubing and the injector head of the CT unit, and then the tensile strength of the flexible tubing after passing through the blowout preventer system should be taken into account. Pressure losses will occur along the entire length of the tubing wound on the drum during the flow of the working fluid, which will depend on the parameters of the fluids used, such as the aforementioned density and dynamic viscosity. The total pressure losses during the flow of the working fluids must also consider losses at the point where the tubing passes through the deflector of the hydraulic head, the rotary nozzle of the hydraulic head, and all pressure losses in the straight sections of the conduit delivering the fluid to the bottom of the well. Increasing the length of the borehole hydraulically drilled will be important from the perspective of hydroabrasion. There are, therefore, a number of different types of relationships, mainly hydrodynamic, mechanical, and strength-related, between the individual elements of the system. Each element of the system has a greater or lesser impact, not only on the other elements but also on the entire system. The effect of the system on the surrounding medium (reservoir rock) causes a response from this medium (borehole diameter, length of the borehole, borehole wall roughness, curvature, and inclination of the borehole), which in turn affects the system and its elements. For example, certain technological parameters of the drilling process will create, among other things, a certain roughness of the borehole wall, which in turn will affect its length and, consequently, the range of such a borehole, resulting from the frictional force between the borehole wall and the pressure tubing. After the development of the rotary drilling nozzle, the first stage of the research program is to start drilling with the designed nozzle on the surface under atmospheric pressure. This will provide data directly related to the drilling capabilities of the rotary drilling nozzle. The distance between the nozzle and the rock helps calculate the hydraulic pressure of the jet, the power of the jet, and the diameter of the jet to enable drilling. In addition, it helps to design the diameter and location of the discharge holes on the face and back of the rotary drilling nozzle. Tests carried out in an atmospheric pressure environment will allow the creation and planning of laboratory tests in the environment of a nozzle immersed in liquid and ambient pressure in the range of 2–12 MPa in a pressure chamber. All laboratory tests are closely related to each other. Ultimately, after the tests are completed, it is possible to infer from the drilled holes the final diameter of the holes and their mutual arrangement in the rotary drilling nozzle. Therefore, the design of each component of the system must take into account a number of relationships between them. These, in turn, form the basis for selecting pumps, nozzles, and conduits for specific reservoir conditions.

2. Basics of Radial Jet Drilling

Drilling techniques for small-diameter boreholes using hydroabrasion require a departure from traditional methods of transferring mechanical energy to the drill bit through a rotating drill string, torque from a downhole motor, mechanically generated impact energy, or indirectly through a hydraulic medium. Utilizing the energy from the jet stream exiting the drill bit nozzles allows for the utilization of previously unused hydraulic energy for hydroabrasion of hard rocks. A similar case arises when abrasive particles are added to the drilling fluid, directly increasing the impact force on the hydro-abraded rock surface. Maurer presented an example of the development of drilling head solutions utilizing rock hydroabrasion methods [11]. The measure of energy required to drill a unit volume of rock during the drilling process is the specific drilling energy. In the case of hydroabrasion, the focus is often on the energy consumed to create a fissure in the rock [11], expressed as the ratio of energy to the product of the depth and width of the fissure and the velocity during the fissure cutting process. In classical drilling, we refer to the total drilling energy TSE (total specific energy), expressed as the sum of the energy rotational motion, the movement of the drill string, and the hydraulic energy required to drill a unit volume of rock during the drilling process [12–15]. In the 1960s, a patent [16] was already granted for a drill utilizing the hydraulic energy of a liquid jet combined with the addition of abrasive material. Steel shot with a diameter of 1.6–3.3 mm and a concentration of 890 N/158.99 L of drilling fluid was commonly used, or alternatively, rounded Ottawa sand grains with a diameter of 0.8–3.2 mm and a concentration of 445 N/158.99 L of drilling fluid. Patents reveal numerous solutions regarding the implementation of hydraulic drilling with a liquid jet, considering various factors.

Requirements for Developing Radial Drilling Technology

When designing hydraulic parameters for radial drilling, the selection of parameters is based on ensuring:

- The ability to drill the rock structure using a high-pressure and high-velocity fluid jet from the nozzle through the front openings,
- The ability to pull the pressure hose directly to the bottom of the borehole that is radially drilled due to the openings directed in the opposite direction to the front nozzles, creating a radial opening.

When selecting hydraulic parameters, it is also important to consider the allowable operating pressure of the system and the length and diameter of the horizontal section. Worldwide, various research is being conducted to determine the hydraulic parameters for radial drilling equipment. The technique of drilling small-diameter holes using hydraulic fracturing requires a departure from traditional methods of transferring mechanical energy to the drill bit, such as rotating the drill pipe, torque from the downhole motor, or mechanical impact energy generated directly or indirectly by hydraulic means. Utilizing the energy of the fluid jet from the drill nozzles allows for the utilization of hydraulic energy, which was previously not directly utilized, to fracture hard rocks.

3. Construction of a Rotary Drilling Head

The process of rock breaking using the energy of a liquid jet requires the use of a suitable device to convert the potential energy of the liquid jet into kinetic energy. For this purpose, a breaking head is used, which is designed to change the static pressure of the fluid into dynamic pressure. This change is achieved by altering the cross-section of the outlet channel through which the pumped fluid is released outside the openings of the drilling rotary nozzle.

Hydraulic drilling nozzles can be divided into:

- Static ones—where the liquid jets and head elements do not rotate,
- Rotating ones—if the rotating element generates a field of rotating jets or internal jet guidance causes swirling, resulting in a swirling motion after leaving the breaking head.

In addition, the hydraulic drilling nozzle may have an option for mechanical rock cutting (if it is designed as a rotating structure and equipped with cutting blades on its rotating element). In this case, the outlet hole arrangement should be designed to serve as a driving mechanism adapted to generate the torque required for rock cutting through slicing.

Custom hydraulic rotary drilling nozzles were fabricated based on the authors' own concept. The heads were subjected to tests of thrust force in atmospheric air and in conditions of a jet submerged in liquid, as well as to investigate their interaction with the drilled rock formation in the form of blocks measuring 300 × 300 × 500 mm. The tool designs proposed below stem from an analysis of available literature solutions of patented inventions. Patents reveal static nozzle solutions and solutions with rotating parts equipped with outlet openings [17,18]. In many solutions, multiple outlet openings are positioned at appropriate angles relative to the head axis. This results in improved coverage of the borehole bottom surface during hydraulic fracturing [8,9,19,20]. Rotating nozzle tools composed of a bearing assembly with dynamic sealing provide more efficient and effective drilling compared to static heads. The bearing assembly, with a static outer body, transfers mechanical and hydraulic loads to the rotating shaft [21]. In some solutions, abrasive material was utilized to enhance the impact force on the bottom of the drilled hole [22]. For the implementation of the planned testing procedure, a research head was fabricated in several variants. The openings in the interchangeable tips were made cylindrical with diameters of 0.4, 0.5, 0.6, 0.7, 0.8, 1.0 and 1.2 mm. The range of jets flowing out of the openings with different diameters was determined during the tests of the hydraulic fracturing efficiency of the test head equipped with one central front opening and six openings made on the side of the cylinder, into which tips with appropriately calibrated diameters of outlet openings were screwed [15]. Given the jet range obtained during the tests of the jet flow from openings of varying diameters, the maximum point is determined along the red line, where the energy of the jet flowing out of the opening allows for volumetric rock hydraulic fracturing, as shown in Figure 3. Projecting this point onto a plane parallel to the cross-section of the rotating head in a direction perpendicular to the axis of the head will allow for the determination of the exit point of the second breaking hole with a designed outlet diameter d. Re-determining the maximum range of the jet flowing out of the opening with the designed diameter and its projection onto a plane parallel to the cross-section perpendicular to the axis of the rotating head will allow for the determination of the exit point of the third outlet hole of the designed rotating drilling nozzle.

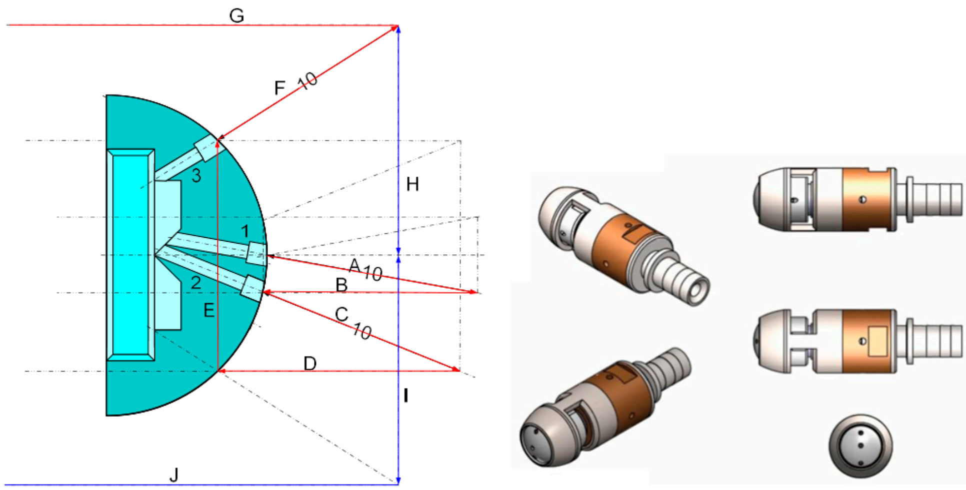

Figure 3. Angle of openings, hydraulic radial drilling hole diameter determination scheme, and an external view of the designed rotary drilling nozzle with its tool face.

The maximum range of the jet flowing out of the designed opening and its projection onto a plane parallel to the cross-section in a direction perpendicular to the axis of the rotating head allow for the determination of the effective range of the jet and the radius from the axis of the rotating head to the diameter of the propagated hole. The design of the rotary head begins by assuming an angle of inclination of the outlet hole 1 with respect to the axis of the rotary head and along line A at the chosen angle plotting a line with the length of the stream reach allowing volumetric mining of the rock equal to 10 cm for a given diameter of the outlet hole (in our case it is a 0.8 mm diameter hole at a discharge pressure P = 40 MPa [15]). Then, from a point 10 cm away on line A from the head face, line B is plotted to the head face parallel to the head axis, determining the location of hole

2. Assuming the same diameter of the outlet holes, line C is plotted again, coming out of outlet hole 2 with a length of 10 cm as before. By dropping a point on straight line C with a length of 10 cm from the head of the rotary head by line D and transferring to the other side of the head by line E, it is possible to determine the outlet of hole 3 on the head of the rotary head. Analogously, as before, assuming the diameter of outlet hole 3 is equal to 0.8 mm, a straight line 10 cm long from the face of the head along line F is determined. From that point on line F, a line G is plotted, which determines, together with line J by plotting lines H and I perpendicular to the head axis, the diameter of the borehole made by the hydraulic rotary head. Considering the above methodology, various rotary tip threads installed at the end of the rotary drilling nozzle, as shown in Figure 4, were prepared in order to study the possibility of propagating a hole of sufficient diameter that will allow the rotary drilling nozzle to move freely into the depths of the hydraulic borehole being drilled.

Figure 4. The beginning of hydraulic radial drilling using the rotary drilling nozzle (the visible rings are caused by the rotational movement of the liquid jets flowing from the outlet openings at various distances between the face tool and the rock).

The geometry of the three cones formed during the initial operation of the test nozzle is shown in Figure 5 below, where successive cones are visible, overlapping as hydraulic fracturing progresses.

Figure 5. Designed rotary drilling nozzle during laboratory research tests.

4. Filed Research Tests

To confirm the feasibility of hydraulic drilling with the designed hydraulic rotary head as shown in Figure 6, a series of laboratory tests were planned, both in atmospheric pressure conditions and in an environment with a submerged jet in fluid. Additionally, tests under surrounding pressure conditions ranging from 2 to 12 MPa were also scheduled. The liquid used in the study was water. Tests were conducted under various temperature conditions ranging from 1–28 degrees Celsius.

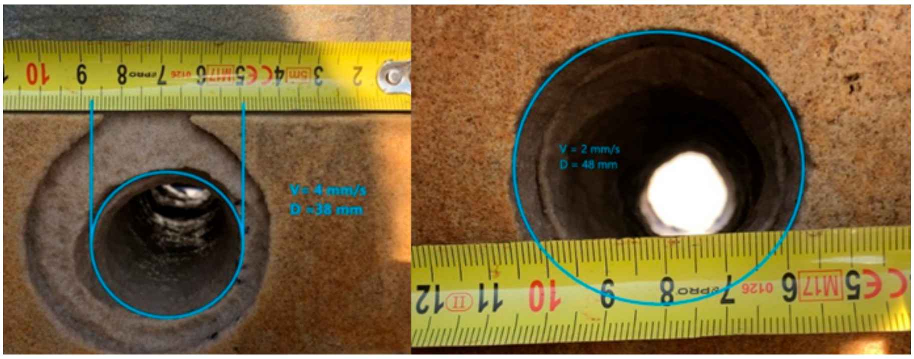

Figure 6. Diameter of boreholes drilled with a hydraulic rotary head at different rates of penetration for sample B1 under atmospheric pressure conditions.

Due to the broad scope of the tests conducted, only fragmented results are presented in this article. The main purpose of the conducted research was to confirm the hydraulic drilling of rock samples using the designed hydraulic rotary head. Two sandstone blocks with compressive strengths of B1 = 24.07 MPa and B2 = 49.64 MPa, respectively, and porosities of 22.41 and 22.21% were subjected to the study. Grain thickness was observed at the level of 0.2–0.3 mm for sample B1 and 0.05–0.1 mm for sample B2. The research tests were conducted at a jet pressure of 50 MPa in atmospheric pressure conditions.

Below are shown the inlet holes made in the B2 rock blocks (Figure 7). The measurement of the diameter of the drilled holes in the tested rock blocks involved overlaying dimensioned photographs with circles closely matching the outlet holes.

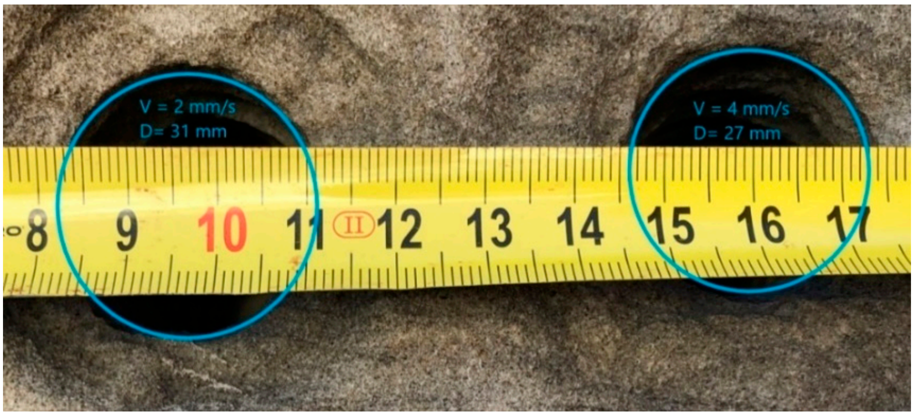

Figure 7. Diameter of boreholes drilled with a hydraulic rotary head at different rates of penetration for sample B2 under atmospheric pressure conditions.

The comparison of the diameters of the drilled holes in sandstone B2 (Figure 7) using a rotary drilling head confirms that a decrease in drilling speed results in an increase in the diameter of the entire drilled hole. This is due to the effective flow time of the fluid jet working with the rock block. The percentage increase in the penetration rate used in the tests for the gray sandstone is 12.9%, benefiting drilling at a speed of V = 2 mm/s. This is, of course, dictated by the extended contact time of the fluid jet with the rock formation being drilled. For sandstone B1 (Figure 6), the increase in the penetration rate when reducing the drilling speed to V = 2 mm/s is comparable and amounts to 14.3%. The recording of the parameters during the tests conducted with the developed nozzle at different rates of penetration is shown in Figure 8 below. As mentioned earlier, the designed hydraulic radial nozzle will allow for drilling with the use of jet stream energy. The possibility of rock cutting depends on various parameters. The penetrability of rock samples is directly proportional to physical and mechanical parameters such as porosity, permeability, and compressive strength, as well as the type and size of the mutual arrangement of rock grain.

If a situation arises where the hydraulic drilling nozzle gets stuck at the bottom of the hole during the drilling process, changing the diameter and angle of the openings on the tool face of the nozzle, according to Figure 3, will allow a deeper borehole to be drilled. Before starting the drilling process with a newly designed tool face, it must be preceded by laboratory tests with a newly developed rotary drilling nozzle.

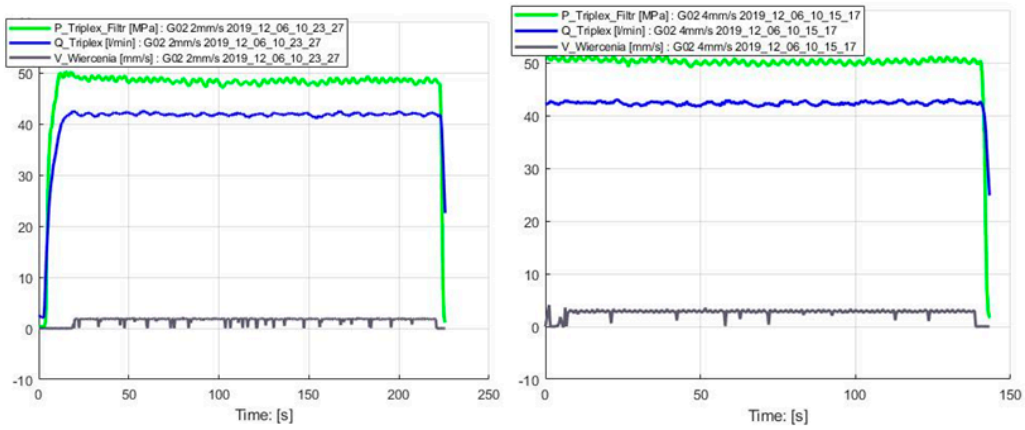

Figure 8. The recording of the parameters during the conducted tests at drilling speeds V = 2 mm/s and V = 4 mm/s.

5. Conclusions

The liquid jet, which has been given significant velocity as it flows out of the outlet holes, is directed towards the rock. If the liquid jet, upon contact with the rock, has sufficiently high energy and creates stress on the rock surface exceeding its breaking strength, a crater is formed. By multiplying the number of jets exiting the head and directing them appropriately, a field of craters is created, forming the bottom of a small-to-medium-sized borehole drilled using the hydraulic fracturing technique. The propagation of the borehole is possible if the movement of the head leads to the deepening of the craters formed. This propagation occurs when the reverse openings of the breaking head generate a thrust force greater than the force pushing the head through the front openings. The force pushing the head towards the bottom of the hole depends on the perpendicular projections of the forces on the surface normal to the main axis of the head. The component forces, however, depend on the jet velocities, fluid density, and cross-sectional areas of the openings. Drilling operations carried out with a hydraulic rotary drilling nozzle under atmospheric pressure conditions at drilling speeds of V = 2 mm/s and V = 4 mm/s have shown that drilling proceeds smoothly, as indicated in Figure 8. There was no jamming of the drilling head during the conducted tests. This indicates a properly designed rotary drilling head, along with the outlet holes, their diameters, and their inclination relative to the axis of the designed rotary drilling head.

Taking the above into consideration, it is also necessary to confirm the proposed methodology for designing the diameter of the outlet holes in the rotary head, as well as their angle of inclination relative to the axis of the designed rotary heads. The methodology presented in Figure 3 allows for determining the maximum diameter of the propagated hole. However, knowledge of the maximum ranges of the fluid jets at the appropriate injection pressure emanating from the outlet holes of the rotary head with different hole diameters is essential. The method for determining the range of the fluid jet at which volumetric hydraulic fracturing of the tested rock formation still occurs is presented in the study [15]. The developed rotary hydraulic nozzle has been thoroughly investigated. Studies in the environment of a submerged fluid jet and under surrounding pressure conditions have been described in another forthcoming publication. The future scope of research will focus on conducting laboratory tests in an environment ranging from 2–12 MPa in a pressure chamber. The study will demonstrate the correctness of the drill head design used and identify possible directions for improvement of the designed rotary device.

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