Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Hydraulic DTH Fluid / Mud Hammers with Recirculation Capabilities to Improve ROP and Hole Cleaning For Deep, Hard Rock Geothermal Drilling

Volker Wittig; Rolf Bracke; Yoon Hyun-Ick

International Geothermal Centre - GZB - Lennershofstrasse 140 - 44801 Bochum - Germany

volker.wittig@geothermie-zentrum.de ; volker.wittig@hs-bochum.de

Keywords: DTH water hammer, hydraulic mud hammer, air hammer, recirculation hammer, multiple phase flow, air lift drilling

ABSTRACT

Geothermal resources tend to be found in deeper and harder geologic formations than typical hydrocarbon reservoirs. Therefore, drilling technologies and processes from the oil & gas field need to be improved constantly to make for more efficient and economic drilling. Drilling speeds or rate of penetration (ROP) of classic drilling technologies, e.g. tricone bits, suffers greatly in deep and hard formations. Thus, there is a great need for tools with higher ROP and low wear to reduce drilling, trip time and cost. Down-the-hole hammers (DTH) using compressed air have successfully been proven for decades in shallow drilling < 400 m depth. To reach greater depth, the working medium must rather be a liquid, due to the compressibility of air and the possible need of drill mud for borehole stability

One of those improvements over the past ten plus years has been the development and application of hydraulic downhole hammer systems at GZB in Bochum and elsewhere worldwide for geothermal, hydrocarbon, and mining drilling applications. However, several disadvantages of these hydraulic, so far mainly clean water hammer systems, held back their widespread use so far. Main hindrances were e.g. water quality of almost clean tap water, missing recirculation systems and thus, no possibility of using drill mud additives for borehole control and improved hole flushing capabilities. With new hydraulic hammer systems being developed in Bochum, Germany and coming onto the market elsewhere, most of these problems have been addressed, if not solved up to now, also pushing their drilling capabilities further down to beyond 5.000 m depth. Work has been done and will be presented here on a summary on past and current hydraulic hammer technologies. Beginning with an introduction to main basic working principles, different hammer types are discussed. The results of recent field tests are being presented. Furthermore, recirculation units for hammer drilling, multiple phase or, respectively, fluid flows, and the potential product of DTD mud powered hammers are being shown and discussed.

These innovative, DTH hammer tools will greatly help the geothermal or other deep drilling industry to make their drilling efforts far more economic, especially but not exclusively, in deep, hard rock drilling situations. Furthermore, hard sedimentary rocks may be drilled much more economically with hydraulic mud hammers being able to be powered by (light) mud and thus, allowing for good borehole control.

1. INTRODUCTION

So called renewable energies are in the head lines of any discussion and future planning these days in the increasingly industrialized countries worldwide. Energy out of geothermal sources tend to take a more and more important role, as it is base load proven, being available 24 / 7, independent of weather and seasonal changes. However, in most places geothermal reservoirs tend to be found in deeper and harder geology than typical hydrocarbon reservoirs up to now. Moreover, dwindling conventional oil & gas resources forces this industry to also look into harder and deeper rock formations for additional hydrocarbon sources (shale and tight gas etc.). Thus, there is an increasing pressure and demand from the applied drilling industry to drill more efficiently into hard rock as being possible up to now, especially with the geothermal industry typically requiring a larger borehole diameter, meaning yet more energy and time required to making the hole.

Over 100 years ago the tricone bit had been thought up and developed, still setting the standard for deep drilling today, with PDC bits in the past few decades improving the ROP some, especially helping in directional drilling. However, drilling in hard, magmatic or metamorphic type rock is still very slow, sometimes less than 1 m / hr. Here, downhole hammer drilling, based on compressed air down-the-hole (DTH) hammer BHAs, has very successfully been used in shallow drilling applications for many years now. There they have proven their rather high ROP compared to PDC or tricone bits numerous times (Riechers 2010). These tools have shown a tremendous increase in ROP, especially in hard rock. Thus, this is the kind of tool to potentially make the deep drilling industry much more efficient.

DTH air hammers, however, will not work in greater depths due to air being compressible and, more important, having a specific density much lower than water or rock, respectively. In opposition to that, hydraulic water / liquid powered hammers have all the advantages and especially high efficiency for breaking rock, even in greater, virtually unlimited depth. For over 20 years now DTH water hammers have been produced and commercially available, having been used and intensely tested at GZB in Bochum. Furthermore, a Swedish manufacturer has used and marketed his product for production drilling in mineral mines as well as specialty applications in shallow to medium deep drilling. One major issue with these hammers so far was the rather high requirement for water quality, needing virtually clean tap water to function long term.

The International Geothermal Centre GZB in Bochum has done extensive field test and industrial type drilling with DTH water hammer systems with various industry partners, finally leading to a new DTH mud hammer system currently being under development at GZB in Bochum.

2. FLUID HAMMER BASIC DRILLING MECHANISM

Hammer or percussion drilling is based on an axially reciprocating downhole piston, which is being activated hydraulically via a pressurized liquid or a gas. The piston then transfers its kinetic energy to the drill bit underneath, which in turn does break the rock. Such a bit is made up of one piece, in the drill face set with tungsten carbide or nowadays even PCD inserts for long life and efficient rock crushing. Hard, even fractured formations being somewhat typical in geothermal formations, like igneous or volcanic rocks or metamorphous sediments, are very well suited for percussion type drilling. Due to their rigidity there is little or no plastic deformation of the rock.

Top drive hammers powered with hydraulic fluids and / or air have been available and used in the industry for over ½ a century. They are known to break rock very fast and efficiently. However, for deeper drilling, DTH hammers are needed to advance into the hole with the bit ahead of the tool string (Riechers; Linke 2012). These are powered by air (→ DTH air hammers) for shallow drilling < 400 meters. Beyond, as mentioned above, liquid powered hammers are needed to offset differences in specific weight and energy losses due to compressibility of gases. These hammers have been under constant development and innovation for the past 50 years with many patents being produced by private companies as well as research institutions. However, only one commercial product has been on the market in the past quarter century.

Hydraulic DTH hammers may be grouped according to their mechanic operation principle (see Fig. 1). The various design versions do have certain pros and cons:

The **Direct Acting** hammer is a very simple construction, requiring a high flow rate and a low differential pressure (e.g. 10 to 30 bars), which is very good. The rather very short life span of the springs is the central problem.

The **Indirect Acting** hammer is also a simple design, having the same attributes as the Direct Acting one, except that the blow energy cannot be controlled during its drilling operation

The **Dual Acting** hammers with valve are rather complicated, fragile designs, featuring a rather high differential pressure (e.g. 180 bars) and a low(er) flow rate. The blow energy may be controlled during operations, and they do not need an internal spring for functioning, which is the critical argument as thus, there is no spring which may fail.

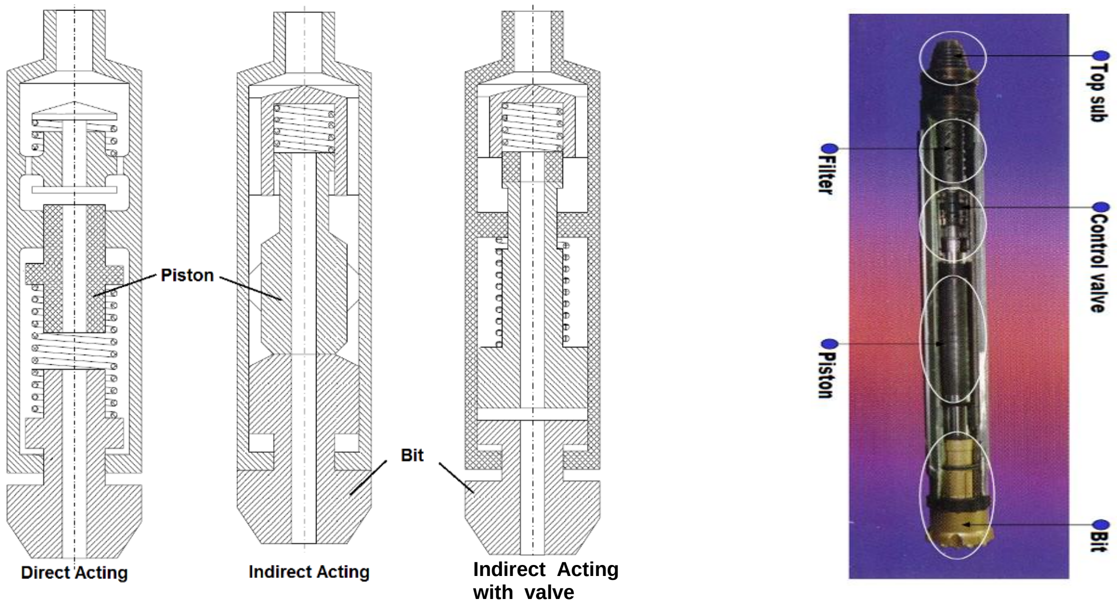

Figure 1: Basic working principles of hydraulic DTH hammers (Lincke 2013) at left, commercial dual acting water hammer with valve on the far right (Wassara AB, Sweden).

The latter one, Dual Acting mechanism with valve for piston control, is the (only) one system that has been commercially produced, available and used on the market so far for the past 20 plus years by a Swedish manufacturer. This is the system that has been investigated and tested extensively at GZB in Germany, eventually leading to a new design.

Normally, intensified liquid, up to now clean water, is being pumped down through the drill rods and the hammer housing, where it activates the piston and thus, changing its hydraulic energy into a reciprocating motion of the piston, which strikes the drill bit and then breaks the rock. The fluid finally exits the hammer at the bottom / drill bit end, then being drill fluid / mud to carry up cuttings and keeping the borehole stable. Depending on the construction of the hammer, some or all of the intensified water will be needed to drive the piston, the rest will just pass through, helping to flush the hole.

3. DTH AIR AND HYDRAULIC WATER HAMMER

A fairly substantial test had been done 2010 in Sweden on a large, shallow geothermal project, comparing commercial DTH air and water hammer drilling systems (Riechers, 2010). In Hässelby, a small suburb of Stockholm, 30 boreholes were drilled, each being 220 to 250 m deep and 115 mm in diameter, for borehole heat exchangers. The prevailing geology there are made of crystalline rocks like Granites and Gneiss. Half of the holes were drilled using an Atlas Copco DTH air hammer TD 40 or COP 44 Gold, powered by an Atlas Copco air compressor with 430 KW engine power to meet the demand for compressed air.

The other remaining holes were drilled using a commercial Wassara W-100 type DTH water hammer, its system being based on a dual acting hammer mechanism as shown on the right side in Fig.1; requiring max. 125 kW engine power. However, used was a far larger WOMA triplex water pump with a 183 kW diesel engine.

The results were as expected and being experienced from years of working with DTH air and water hammers. The data collection focused on ROP, hole quality (→ here absolute deviation from the vertical line) and prime energy consumption for the pump and compressor.

Fig. 2 on the left shows both ROPs from air and water hammer dropping hyperbolically to an average speed value, which would eventually drop off sharply towards zero for the air hammer, whereas the water hammer remains working with a fairly, just slightly with depth decreasing ROP towards any arbitrary depth. Below 190 m ground water entered the boreholes, which is clearly visible in a sharp decline in the air hammer`s ROP, whereas water hammer`s performance is not fazed by it at all. Overall was the air hammer`s ROP at 0,69 m/min, the water hammer`s avg. ROP was 0,52 m/min. However, air hammer performance suffers greatly in saturated, wet hole conditions and also with increasing depth, as Fig. 2 shows.

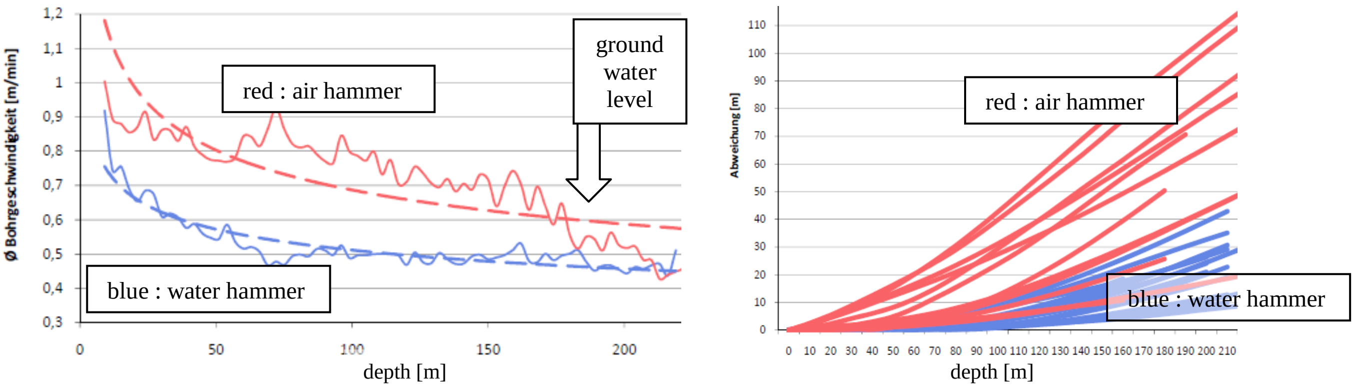

Figure 2: comparison DTH air and water hammer in Sweden (Riechers, 2010), ROP (m/min) versus depth (m) on the left; absolute borehole deviation [m] from vertical versus depth [m] on the right.

Hole quality, which here had been measured only in form of deviation from the aimed at, straight vertical borehole axis, proved to show a clear advantage of the water hammer tool (blue lines in Fig. 2 on the right). The avg. deviation was under 10 %, meaning a max. 10 – 20 m distance from the vertical line. The air hammer had on avg. a deviation of 35 %, reaching even 110 m deviation on a 220 m borehole once. The explanation is here that a water tool may be guided much tighter, as it needs less of an annulus for water and cuttings to exit the hole. Air expands drastically after passing through the hammer, and the cuttings of an air hammer are much larger than those of a water hammer.

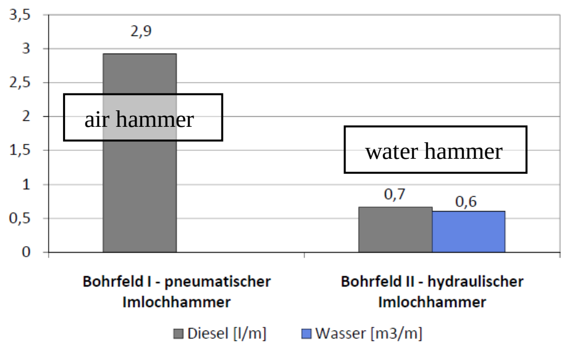

Figure 3: comparison DTH air and water hammer in Sweden (Riechers, 2010), consumption of Diesel (liter) per drilled meter for the air compressor (left) and the water pump (right), incl. the water consumption for the water hammer.

Another factor was the consumption of primary energy for the drilling process, here only the diesel amount for compressor (air hammer) and water pump. The drill rigs do the same amount of work for both BHAs and thus, have not been accounted for. On average, the air hammer needed over 4 times the amount of diesel (2,9 L diesel/m of energy) per drilled meter than did the water hammer (0,7 L/m drilled depth), based on same hole diameter and geology (Fig. 3). Therefore, the air hammer drilled appr. 30 % faster, but only in dry hole conditions and more shallow depth. However, the air hammer did use a compressor which had over threefold the installed / required power than the water hammer`s pump did (430 kW versus 125 kW required). This shows very impressive how inefficient DTH air hammer drilling is. But it also proves how fast DTH hammer drilling performs in rather hard, crystalline rock, drilling along at roughly ½ m/min, in case of hydraulic water hammers regardless of depth and ground water conditions.

4. WATER HAMMER DRILLING : DRILL FLUID CONSUMPTION AND RECIRCULATION

At GZB in Bochum, Germany, during 2012 and 2013, good 4.000 meters had been drilled in total, devided in 20 holes, each 200 m deep, using a commercial Wassara water hammer system for installation of geothermal ground loops, while looking at energy and water consumption, tool wear, directional drilling and mud cleaning / recirculation possibilities. In contrast to the drilling campaign in Sweden in 2010 (chapter 3), the geology at GZB in Bochum is much softer, being sedimentary rock, the so called “Ruhr Carbon”, with changing layers of sand / silt and clay stone, but rather folded up with steep banks making for numerous anti- and synclines, and thus, meaning a good challenge for drilling operations (Bussmann et al., Poletto and Wittig). In this folded geological scenario, GZB drilled, using a brand new Hütte HBR 207 GT drill rig, at a constant angle of 10 to 15 degrees, making for a small, elliptical drill pad, from which the boreholes were advanced in a star like pattern to the outside and downwards (→ “GeoStar”, Bussmann et al.). The water table at this location was at about 8 meters BGS, being somewhat fragmented.

The BHA consisted of a commercial Wassara W-150, 6 inch water hammer system on 6 inch OD drill pipes, with a 7 ¼ inch (185 mm) drill bit (→ 5/8 inch annulus), which had been designed and made by GZB in Bochum.

Figure 4: configuration of the DTH water hammer BHA including the 6 inch Wassara W-150 hammer and the 7 ¼ inch drill bit designed by GZB, clearly visible are the guiding ribs on the hammer housing (left) for high accuracy.

During this project, the focus was on improving a next generation DTH liquid hammer in such a way that it could be run with mud as well. Therefore, separate time measurements were taken for drill time (ROP) and hole cleaning. The results suggested that the current 6 inch Wassara water hammer system, requiring between 330 and 600 L/min of flow, would need more water to run through it, in order to carry up cuttings fast enough for its rapid drilling speed of appr. 0,9 m/min. The avg. upward mud speed in the annulus was between 0,7 and 1,2 m/min, being above avg. for normal mud rotary drilling.

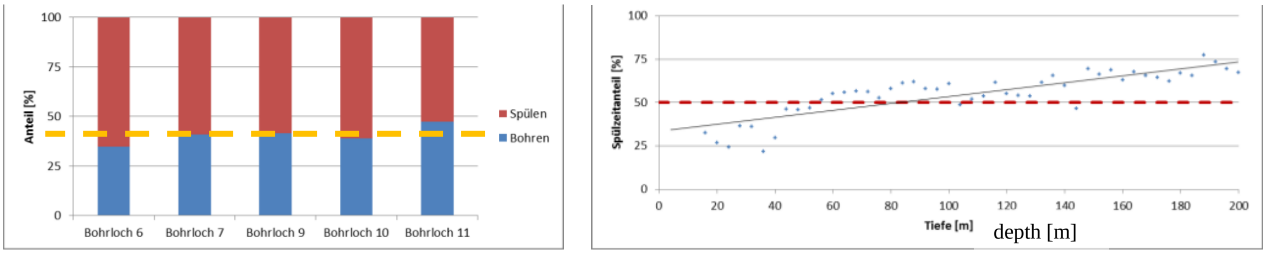

Figure 5: consumption of water for drilling (ROP) and hole cleaning: on avg. only 40 % of the water (blue) is used for drilling, rest for hole cleaning (left); water amount for hole cleaning (%) increasing with depth (right).

The avg. drill speed of 0,9 m/min was rather high for 7 ¼ inch open hole drilling, proving once more the unmatched drilling performance of hydraulic DTH hammers for deep, hard rock drilling. The speed does drop off some with depth, as will be seen later on as well. However, the increasing time needed for hole flushing has a much greater effect on total drill time (Fig. 5 right). This proves that the hydraulic hammer does drill very fast and thus, breaks lots of material, which needs to be flushed out. In order to do that simultaneously as the hammer (bit) breaks / cuts the rock at ROP, a lot more water or mud flow would be required. But as the liquid flow through the hammer is limited, out of good reason, it can carry out only so many cuttings while actually drilling. The rest needs to be flushed out of the hole after the actual drill work (→ bit on bottom) has been completed. That is then what’s referred to as time for flushing the hole. Another limitation here is the requirement for the use of clean water through the hammer and thus, limiting the carrying or floating capabilities of the return water or “mud” to only its uphole velocity, which depends on the size and service state of the hammer, plus of course the dimensions of the drill pipe and hole, giving of course that the pump delivers enough flow.

This leads to the conclusion that a future hydraulic DTH hammer drilling system also needs more focus on carrying up the cuttings at the same speed as ROP, becoming increasingly a point with increasing depth. This requires circulating systems to limit the amount of fresh water consumption, and also somewhat drill mud compatible DTH fluid hammers.

The low diesel consumption of 1,5 Liter per drilled meter compares well to earlier results of 0,7 L/m out of 2010 in Sweden (Riechers, 2010), therefore making double the hole size here at GZB this time.

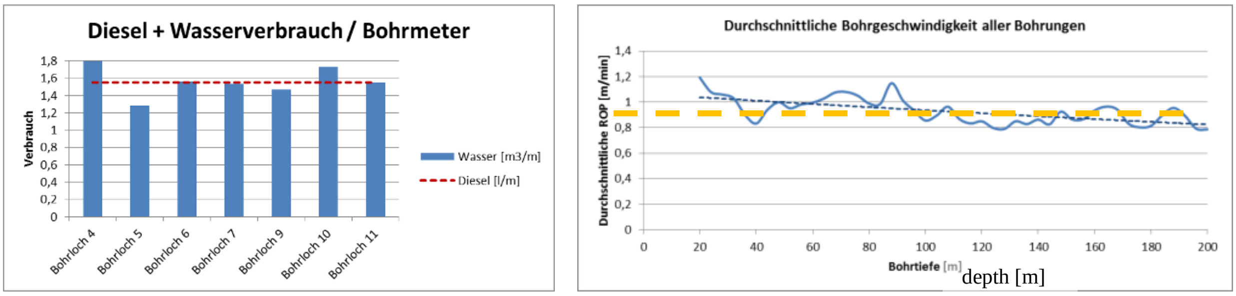

Figure 6: diesel and water consumption of 6 inch Wassara W-150 hammer with 7 ¼ inch drill bit (left): about 1,5 L of diesel or m³ of water per drilled meter were consumed; avg. ROP was 0,9 m/min, slightly decreasing with depth (right).

Another focus during this project was on drill water treatment, recycling and possible recirculation. All three are necessary to some level, depending on how the water will be disposed of or whether it shall be recirculated. At GZB, a Wassara hammer had been used and tested, requiring basically clean water with less than 0,015 % of total, dissolved solids, while the max. grain size should not exceed more than 20 micron (= 0,02 mm). The hammer works in a flow through set up, meaning all water entering the hammer flows up the annulus, out the borehole and needs to be contained or disposed of. The first tests were done simply disposing the water, meaning e.g. for a 200 m deep hole, using the 7 ¼” bit on 6 inch hammer as above, appr. 300 m³ of water had been run through the hammer and disposed of. If water is cheap and plenty, and disposal or surface percolation not a problem, then this set up works very well. However, in most cases, local wastewater systems and plants only accept limited amounts of solids, requiring pre cleaning. Fig. 7 (right) shows the drill site set up with 1st sedimentation unit allowing sufficient cleaning of the drill water incl. returns to be then disposed of in public sewer lines.

Figure 7: drill site (right) at GZB during DTH hammer drilling, first sedimentation container (white) always in use, second stage cleaning (optional) on left side including lamella cleaner and flocculant station.

The gravity cleaning via sedimentation container / station may be optimized using a filter system made up out commercial big packs, which are being set up on site in a container (Fig. 8). That system, however, recycles 1st of all the drill cuttings, not the water. But the cuttings of DTH water hammers are rather homogenous and favorable in size, so further (re)use in surface and road construction or landscaping etc. depending on geology are very welcome. Thus, disposal cost and logistics will be saved and reduced.

Figure 8: drill site at GZB during DTH hammer drilling : sedimentation container is lined and set up with commercial big packs for full recycling of drill cuttings; sample of cuttings and sacked material (right).

The real challenge yet remains for further cleaning of the drill water after the 1st sedimentation stage to the above mentioned standards in order to recycle the water and run it in a full, closed loop, with much or all of the water being reused. Two options are possible, either to clean the water really good or / and to build a hammer that may tolerate more solids in the water. In deep drilling practice today, on both ends needs to be worked on, out of several reasons. Deep drilling requires the use of drill mud for borehole control and other tasks, which is being treated and maintained on site to the required standards of each borehole. A future DTH mud hammer should be able to meet at least a "lighter" version of such mud conditions with an acceptable service life.

During the above hammer drilling tests at GZB, work has been done on cleaning the drilling water sufficiently to meet the hammer`s high requirements for almost clean water. Together with the Swedish company Wassara AB, a 2nd stage lamella cleaning container had been added to the regular 1st stage (see Fig. 7 on the left), allowing for the water to be treated enough for full recycling in that given geology. The cleaning had been sufficient, but only by adding flocculants at the end in order to eliminate most of the increasing amounts of fines in the water, adding up to far more than 0,015 % total solids otherwise. A 5 micron / 0,005 mm filter run at the very end for safety hardly caught any more particles, leaving a rather clean liquid for full recycling. However, that lamella station having been used at GZB with 20 m³ in total volume was too small in size for the hammer flow of up to 36 m³/hour. In order to handle and clean the full flow of such a 6 inch hammer, it would need to be up to three times larger. That also proves that cleaning drill water means equipment, logistics, investment, operational cost etc. Running equipment like desilter / desander or / and centrifuges like in deep drilling opertions is possible and has been done, but it's even more expensive. However, there possibly seem to be now commercial DTH water / fluid hammers on the market providing full recycling capabilities with their hammer drilling system.

5. RECIRCULATION AND MULTIPLE PHASE FLOW TO IMPROVE DEEP DRILLING CAPABILITIES

During 2013 and 2014 private manufacturers of DTH water hammer equipment and GZB have pushed to new limits regarding drilling depth, speed and new drill fluids, including full circulation and 2 phase flow possibilities. A deep drilling project in South Korea proved excellent ROP using an 8 inch DTH water hammer system with a built in accumulator system down to meanwhile 5.000 meters in hard granite (Fig. 9 and 10). The ROP decreased during the first 1 to 1½ km down to avg. 15 m / hr, but then remained steady over 10 m/hr down to 4.500 meter depth. The system had been specially designed and built to be used with recirculated water and also some air compressed into the water (Fig. 9 right).

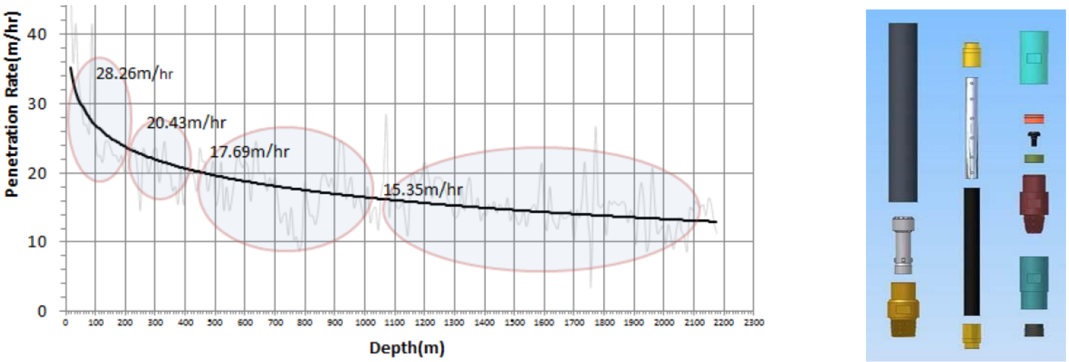

Figure 9: Results from drilling with 8 ½ in bit on an 8 in DTH water hammer with two phase flow (right) in very hard granite, drill speed ROP [m/hr] versus depth [m], ROP remained over 10 m/hr down to 4.500 meters, South Korea.

For the geologic conditions in that type of granite at the South Korea test site the cleaning and recirculation worked sufficiently well. A specially designed and built lamella cleaner is based on gravity cleaning, requiring no external power input other than transfer pumps. A very light drill mud, based on polymer additives, had been used to help carry up cuttings in greater depth.

Figure 10: Test drill site in South Korea during DTH water hammer drilling down to 5.000 meters (right), drill mud treatment system for DTH mud hammer recirculation with sedimentation and lamella cleaning containers (left).

Another very important feature of this new hammer system was the use of a small volume of air in the intensified fluid being run through the hammer. This was supposed to increase the efficiency of the DTH hammer, having a built in accumulator always being automatically pressurized up to ambient downhole pressure. Gas type accumulators are normally installed and run in any top drive surface hammers that are powered with a non-compressible liquid, helping and ensuring in hammer performance. This feature has so far been missing on downhole hammers due to a constantly changing pressure regime inside and outside of the hammer. However, up to this time no detailed testing has been done to compare DTH hammers with and without a dynamic, built in accumulator.

The other huge advantage of some trapped air in the hammer fluid is its expansion after passing through the hammer at depth and moving up the annulus towards surface. Here it decreases the density of the combined fluid + air mix and thus, tremendously helps in carrying up the cuttings, much like an air lift system. This has been the most immediate and visible advantage of this drilling system as it has been used to drill down to 5.000 meters in hard granite. The drilling tests at the GZB site in Bochum (Chapter 4) revealed the problem with current clean water hammers, requiring increasing time and fluid with depth to carry up the cuttings. Having set up a quasi air lift system parallel to hammer drilling definitely decreased the time spent on hole cleaning before.

However, one problem is to mix the air into the drilling fluid at surface at pressure, as it needs to be compressed together with the water. That requires a special pump, as standard triplex piston or plunger plumps don´t like gasses in the fluid, the efficiency drops dramatically, and cavitation and other issues may damage the pump, making for very short service life. Such a pump is currently under development in the industry and at GZB. A prototype pump may be available soon at GZB for further testing of these air lift hammer systems with built in accumulator.

6. STATE OF THE ART AND FUTURE DTH LIQUID HAMMER SYSTEMS

There has been a tremendous amount of work done on the area of hydraulic DTH hammer systems (Deutsche Steinkohle et al; Marx et al; Teodoriu; Amoco; Fernandez). Below is a short compilation of what has been done or what lies ahead for the coming years. To be mentioned at first is the NEXT drill project started in Norway, mainly organized by SINTEF and IRIS. The objective is to find innovative methods for faster drilling in hard rock, as it is prevalent there in Scandinavia, much like in South Korea. As to be expected are hydraulic DTH liquid powered hammers part of their developments. A so called Pen-Rock hammer is being designed within this project as a high frequency tool to run at appr. 100 Hz, with an hydraulic efficiency of 80 %, yielding a theoretical ROP of 35 m/hr in granite. This hammer is in planning stage only, no prototype has been run nor tested yet.

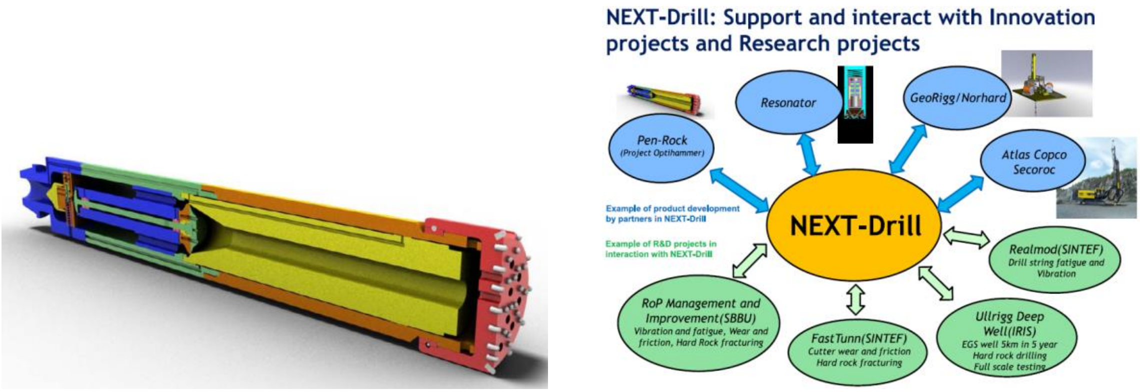

Figure 11: Future high frequency hammer (left); overview of the Norwegian NEXT drill consortium and projects (right).

Another future development within this NEXT drill project may be a so called Resonator percussion hammer, where a linear motor coupled with an electro mechanically oscillating piston makes for very high frequencies of up to 200 Hz. Increasing frequency is commonly linked to increasing ROP, explaining why some developments are looking for an increase in piston frequency.

Baker Hughes has successfully used hydraulic hammer like systems, mostly for horizontal coiled tubing type milling operations. Gaining extended reach with such a tool seems to be one very positive result (Castandea et al., 2011). The Baker hammer tool controls its piston motion by making use of the so-called Coandă effect, making for fluidic directional control without mechanical and thus, wear and tear.

NOV, National Oilwell Varco, is offering now a hydraulic fluid hammer supported BHA, featuring increase in ROP, extended reach, reducing stick-slip situations etc. It may be used with both, roller cone and PDC bits. However, it is not clear if it is a direct flow through activated hammer system, or whether it is a system utilizing an encapsulated percussion activator, being powered 2nd step electrically or hydraulically out of drill mud`s hydraulic energy via a generator.

This is a concept having been investigated in part at Novatek in Utah in 2005 (Fernandez et al.). There, at least with support of some electrical power, a DTH mud hammer unit is activated an run inside the BHA. This had been a collaborative effort with the US Dep. of Energy (DOE), having been involved in a few projects to improve ROP and efficiency in rock drilling. But the hammer system never evolved into an industrial product.

However, at GZB in Bochum there currently is work underway on a new DTH mud hammer concept. One idea there is powering a shielded hammer or vibrator section in a secondary circuit with power generated out of the mud stream, such that the hammer is run in a separated, controllable and clean environment, independent of the drill mud conditions. This may be one favorable solution to have a true mud compatible DTH fluid hammer drilling system for deep drilling, allowing full borehole control and transport of cuttings.

7. CONCLUSION AND OUTLOOK

Hydraulic DTH fluid hammer drilling has been looked at and used for about ½ a century. From the industry standard tools like top drive, surface hammers powered with hydraulic oil, as well as downhole air hammers, being powered by compressed air and advanced to depth together with the bit and rod string, their powerful, efficient performance is very well known, together with a high ROP. That knowledge has been driving the work to design a robust, hydraulic downhole fluid hammer to be powered with mud for deep drilling applications, and having acceptable service intervals.

As of now, there is only one DTH water hammer, may be two at most by publication of this paper, industrially available on the market to be used of the shelf for deep drilling including service and support etc. Hole size may range from 2 inch up to max. 12 inch for the time being. The hammers are best powered with clean water, even though recirculation systems are on the way and already available. GZB in Bochum has done extensive testing and drilling work with such an industrial, 4 and 6 inch DTH water hammer system. But there was no hard data taken yet on comparing tool life and performance from hammers running with clean water and those being run with recirculated water. Depending on the drill site, borehole depth and availability of resources and logistics, drilling with clean or recirculated water through a hammer will be economically feasible, even if the hammer service life is still less than average.

The work at GZB has shown that future hammers ideally should operate with a lower differential pressure, e.g. < 60 bar, making for far easier sealing within the hammer and less delicate parts and surfaces. On the other hand, the testing also proved that more flow relative to the fast drill speed would be optimal, in order to having a better equilibrium between making cuttings and transporting them up the annulus to surface. That also results in the same net hydraulic power.

The water hammer manufacturers so far may have kept the water flow to a minimum, as it had to be discarded after use. Because more water flow meant higher cost, plus a poor environmental image. Therefore, the future hydraulic DTH hammer needs to tolerate more solids in the water, allowing for recirculation. Then the amount of flow doesn`t matter, as it is normal in deep drilling, mud rotary operations. Furthermore, the additional use of drill mud is needed for hole cleaning and borehole stability.

In terms of hole cleaning while drilling, the tests in South Korea did show very impressive results. When borehole stability is not a problem, like in Granites etc., the air lift effect of small volumes of compressed air mixed into the fluid does improve cutting transport tremendously, further improving hammer performance. However, hammer and especially the pump have to be set up for that.

Even the largest service and drilling companies like Baker Hughes and NOV have investigated into hydraulic hammer drilling and even published a few results. Their products seem to be already tolerant towards the use of drill mud, however nothing is known yet about life span and tool wear. However, it means that DTH fluid / mud hammers are in the focus of being one, may be even the tool at the moment, to really enabling the drilling industry towards making more economical, deeper boreholes. That in turn could also help the geothermal industry to easier tap the deep resources.

ACKNOWLEDGMENTS

Authors thank the entire GZB staff and students for their support and work on this hammer project. A very special thank you goes to our drilling team for their long endurance and patience during the hammer drilling operations in 2013 and 2014.

REFERENCES

Bussmann, Gregor et al., International Geothermal Centre -GZB- : GeoStar – a Scalable Borehole Heat Exchanger System for District Heating Systems and Constricted Large Urban Infrastructures; Proceedings World Geothermal Congress 2015, *In Press 2015*

Castaneda, J.C. et al., Baker Hughes (2011) : Coiled Tubing Milling Operations - Successful application of an innovative variable-water hammer extended reach BHA to improve end load efficiencies of a PDM in horizontal wells; *SPE paper 143346, Coiled Tubing conference*, The Woodlands, TX, 2011.

Deutsche Steinkohle AG, 2002 : Entwicklung eines Seilkernsystems mit hydraulischem Imloch-Bohrhammer für Kernbohrungen / Development of a wireline coring system using a hydraulic downhole hammer for core drilling; *final report for the DSK research project* (DSK Kenn- Nr. : 0294 0000), Herne, Germany (2002)

Fernandez, J. et al. (2005): Integrated drilling system using mud actuated down hole hammer as primary engine, *final research report #* 34365R0; DOE award # D E - F C 2 6 - 9 7 F T 3 4 3 6 5; 2185; Novatek, Provo, UT 84606, USA (2005)

Marx,C. et al (1992): Untersuchung zum Leistungsbedarf hydraulischer Bohrhämmer und die Ermittlung der Bohrleistungen im Hartgestein / Investigation of power requirements of hydraulic DTH hammers and acquisition of drill speed in hard rock; Celle, Germany, *DGMK-Tagungsbericht* 9203, Frühjahrstagung, 14. u.15.Mai 1992.

Lincke, J.D., 2013: Systemvergleich und Wirkmechanismen verschiedener fluidbetriebener, hydraulischer Imlochhämmer / System comparison and mechanisms of various, fluid powered downhole hammers. *MS Thesis, University of Applied Sciences, Bochum*, Germany (2013)

Poletto F. (OGS), Wittig V. (GZB), Schleifer A. (OGS), Bracke R. (GZB): Hydraulic DTH Fluid Hammer Drilling as a Seismic While Drilling (SWD) Source for Geothermal Exploration and Drilling Prediction; *Proceedings World Geothermal Congress 2015, In Press* 2015

Rector III J. W., and Marion B. P.: The use of drill bit energy as a downhole seismic source. *Geophysics* 56, 628-634 (1991).

Riechers (2010), Innovatives hydraulisches Bohrverfahren für die oberflächennahe Geothermie als Alternative zum pneumatischen Bohrstandard / Innovative hydraulic drilling process for shallow geothermal applications as alternative to the pneumatic standard*; BA Thesis, Bochum University of Applied Sciences* – International Geothermal Centre, Bochum, Germany (2010)

Teodoriu, C. (2011): Use of Downhole Mud-driven Hammer for Geothermal Applications. TU Clausthal. Proceedings SGP-TR-194, *Thirty Sixth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California (2011)

Tuomas; Göran (2004): Water Powered Percussive Rock Drilling - Process Analysis, Modelling and Numerical Simulation*; PHD thesis*, *Luleå University of Technology*, Dep. of Civil and Environmental Engineering, (2004) ISSN: 1402-1544 • ISRN: LTU - DT -- 04⁄58 -- SE

Vollmar D., Wittig V., Bracke R.: Geothermal Drilling Best Practices: The Geothermal translation of conventional drilling recommendations - main potential challenges; *IGA Academy report, international Finance Corporation IFC*; International Geothermal Centre Bochum – GZB- , Germany (2013).

Wittig, V. and Bracke R.: DTH Fluid Hammer Drilling Developments and latest R&D activities at GZB in Bochum; International Geothermal conference *GeoTherm in Offenburg*, Germany (3-2012).

Wittig, Volker; Bussmann, Gregor; Tünte, Henry; Maeggi, Kurt (International Geothermal Centre - GZB): DTH Fluid Hammer Bohrsystem für geothermische Anwendungen in (tiefen) Festgesteinen / DTH fluid hammer drilling system for geothermal applications in deep, hard rock; *Der Geothermiekongress / int. geothermal congress, Karlsruhe*, Germany (2012)