UTILIZING COILED TUBE RIG FOR MINERAL EXPLORATION APPLICATION

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ABSTRACT

Mineral exploration is in a race to employ drilling technology that can perform the exploration and drilling investigation in a fast and inexpensive manner. After an extensive study of the available drilling technologies in the market, coiled tubing was chosen as a tool to be employed for mineral exploration due to its flexible mobility and ease of operation with a minimum number of personnel. Since coiled tubing technology is primarily used in the oil and gas industry, it was important to re-design the coiled tube rig to drill hard rocks in a fast and feasible manner. The main requirements were to drill the smallest feasible hole diameter and go as deep in the ground as possible, in the shortest reasonable time. The drilled rock particles, cuttings, are to be collected and analysed at the surface for their metal mineral contents. The process also needs to be repeated multiple times at different locations for mapping, without the need to change the tube on the rig due to failure or potential failure. The focus of the new designed coiled tube, for drilling and mineral exploration, is three fold. First is to increase the rate of penetration in drilling by designing a small high speed turbo motor. Second is to determine the controlling parameters of cuttings transport to effectively lift the cuttings to the surface for analysis and third is to minimize the overall weight of the rig for manoeuvring and prolong the life span of the coiled tube string. In this paper, a small downhole turbo motor, 5cm outer diameter, is designed to achieve a rotation speed of up to 10,000 rpm to fit on a small bit, coiled tube drilling assembly. The motor design utilised multiple finite volume and finite element analysis softwares for fluid flow study and fluid structural interaction analysis. The paper is also introducing the concept of a flow slurry loop that is designed to lift the cutting particles to the surface for mineralisation analysis. The controlling parameters of the cuttings transportation are the particle's physical properties such as size, density, concentration and shape, as well as the rheological properties of the carrying fluid, drilled hole angle, as well as the fluid flow rate and flow dynamics within the annulus gap between the coiled tube and drilled hole. Such parameters are addressed via experimental work as well as numerical analysis. The paper is also presenting the selection and testing procedure of the material type for the coiled tube string. The tube needs to be light in weight for overall rig weight and its transportability. The tube is also required to drill several dozens of investigation holes before failing due to fatigue. A fatigue bending machine is designed to test the endurance limit of candidate materials for coiled tube strings and a performance index methodology is followed for material selection of the optimum material. The coiled tube rig is designed to be light in weight for transportation and relocation. It is also required to speed the drilling operation with the minimum footprint and reclaim the drilled rock particles for mineral composition analysis at the surface.

KEYWORDS

Coiled Tube, Mineral Exploration, Drilling, Turbine Motor, Flow Loop, Material Selection, Carbon Fibre, Fatigue

INTRODUCTION

Coil tubing (CT) technology is primarily used in the oil and gas industry for work-over applications, well logging, drilling and other applications as described by Jaworsk (1992). In order to utilise CT technology for mineral exploration operations, it requires drilling multiple, deep, small size boreholes as fast as possible to reach a potential ore body. The drilled rock particles are to be collected at the surface for various analyses and most importantly for their mineral content.

One of the attractive characteristic of CT in drilling is its fast operation relative to other conventional drilling methods. The rig up is quick and the CT system is mobile. Therefore, the cost per drill hole would be cheap and the exploration and mapping of an ore body will be feasible and relatively fast. However, the CT rig needs to be re-designed for the mineral exploration applications. Drilling hard rocks in a fast manner, gathering the drilled particles for analysis, and having a mobile, durable rig are the main parameters that are considered in this study to make the system feasible.

The first objective for re-designing the CT focuses on the drilling driving power. The input drilling power needs to achieve the highest possible rate of penetration. Therefore, a small high speed turbo motor is designed to attain a high revolution per minute with the smallest outer diameter that can fit on a small weight on bit CT drilling assembly, as explained in more details later in this paper.

The second objective is to understand the best operating conditions that would assist in collecting all the drilled particles to the surface. Since the drilling operation is meant to collect and analyse the drilled rocks (cuttings) for their mineral contents, a slurry flow loop is designed to understand and study the parameters that will affect the lifting and transportations process of the cuttings to the surface. Some of the parameters that would affect the performance of the flow loop are the particles physical properties, rheological behaviour of the cutting slurry as well as the drilled hole angle, mud flow rate and flow dynamics in the annulus gap between the CT and the drilled hole. Rheological analysis of the drilling mud and percentages of cutting added to the mud are addressed in this paper. The design of the flow loop experimental setup is presented.

Finally, to achieve a light rig that would be easy and cheap to relocate, as well as a durable CT string, a study is performed for an alternative CT material. The current CT strings are made of high strength low alloy (HSLA) steel. Besides its heavy weight, the CT is known to have low fatigue life due to the multiple bend and flattening events during operation (Avakov, Foster, & Smith, 1993). Therefore, Jaworsky and Wolliams (1993) investigated composite materials such as carbon fibre and glass fibre as options to replace the steel tube strings. Carbon fibre tubes were recently tested at the DET-CRC training facility (Fuller, 2012; DET-CRC press release, 2012). In order to confirm that composite material is the optimum choice for the CT drill rig application, a performance index method (Farag, 2007) is used to assess possible material replacement for the HSLA steels and a fatigue testing machine is designed to test and evaluate the candidate materials.

TURBINE DOWN-HOLE MOTOR DESIGN

CT cannot rotate and therefore a down-hole motor is needed to provide mechanical power and rotation to the bit. Mokaramian, Rasouli, and Cavanough (2012) evaluated the available motors for deep mineral exploration and they concluded that high speed turbodrill (turbine motor) is the best choice for small size CT drilling for hard rocks. The advantages of turbine motors are their high efficiency for a low weight on a bit drilling system, high quality, and smooth borehole creation because they generate minimum vibration during drilling.

The down-hole turbine motor (turbodrill) is composed of two sections: a turbine motor section and a bearing section which are thrust-bearing and radial support bearing. The turbine motor is a type of hydraulic axial turbo-machinery that has multistage rotors and stators. It converts the hydraulic power provided by a drilling fluid, which is pumped from the surface, to mechanical power as it is diverting the fluid flow from the stator vanes to the rotor vanes. The fluid runs through the turbodrill and the bit nozzles where it cools the bit and removes the cuttings generated under the bit. It finally carries the cuttings inside the annulus between the CT and the hole to the surface. The energy required to change the rotational direction of the drilling fluid is transformed into rotational and axial (thrust) force. The energy transfer is seen as a pressure drop in the drilling fluid. The thrust is typically absorbed by thrust bearing. The rotational forces rotate the rotor relative to the housing. The bearings, both radial and axial thrust, maintain the appropriate turbine blade position which generates concentric rotation. In practice, multiple stages are coaxially stacked to achieve the desired power and torque. Other fluids that possess different rheological properties as non-Newtonian fluids are simulated by Mokaramian, Rasouli, and Cavanough (2013).

Numerical Simulation of Fluid Flow through Turbodrill

In this study, the fluid flow analysis through a small diameter turbodrill, ANSYS TurboSystem tools together with ANSYS CFX for computational fluid dynamics (CFD) simulations were utilized to investigate the turbodrill performance. The flow field using CFD simulation is calculated based on the Reynolds-Averaged Navier–Stokes (RANS) equations which are derived from the governing Navier–Stokes equations. For an incompressible Newtonian fluid such as pure water, the RANS equations are expressed in tensor notation by the following:

$$\rho\frac{\partial U_i}{\partial t}+\rho U_j\frac{\partial U_i}{\partial x_j}=\rho\overline{f}_i+\frac{\partial}{\partial x_j}\left[-p\delta_{ij}+2\mu\overline{S}_{ij}-\rho\overline{u_i'u_j'}\right], \tag{1}$$

where: U is the velocity vector, ρ is the fluid density, f_i is a vector representing external forces and δ_{ij} is the Kronecker delta function (δ_{ij}=1 if $i=j$ and δ_{ij}=0 if $i\neq j$). Also, S_{ij} is the mean rate of strain tensor which is defined as:

$$\overline{S}_{ij}=\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right). \tag{2}$$

Designing a hydraulic multistage turbodrill, it is assumed that each turbodrill stage is identical. In other words, the flow rate, pressure drop, rotary speed, generated torque, and power transmitted to the shaft are the same for each stage. Therefore, a complete design of one stage is performed and the turbodrill performance is calculated for multiple identical stages, stacked and connected to the turbodrill shaft. In this paper, only one turbodrill stage model is considered with shroud (housing) and hub (shaft) diameters of 50 mm and 40 mm, respectively. Consequently, the span wise height will be 5 mm for this model. The number of blades on the stator and rotor are 20 blades each, with no shroud tip between blade and housing, where the blades are connected to the housing. The drilling fluid is clean water, a Newtonian fluid. The default water properties are considered as per the CFX software.

<u>Simulation Results:</u>

The results for one stage turbodrill model with water flow rate of 4L/s is presented as power and torque versus rotation speed as shown in

Figure 1. The maximum power and torque is achieved at approximately 6,000 rpm, which is equivalent to 725 W and 1,152 N.mm, respectively. The runaway turbine speed is almost over 11,000 rpm, and stalled torque is about 2,320 N.mm. Similar runs were performed on non-Newtonian fluid that followed the Hershel-Bulkley model, at similar flow rate. Results showed the maximum stage efficiency at 5,000 rpm that is equivalent to 518W and 990 N.mm power and torque, respectively (Mokaramian et. al., 2013).

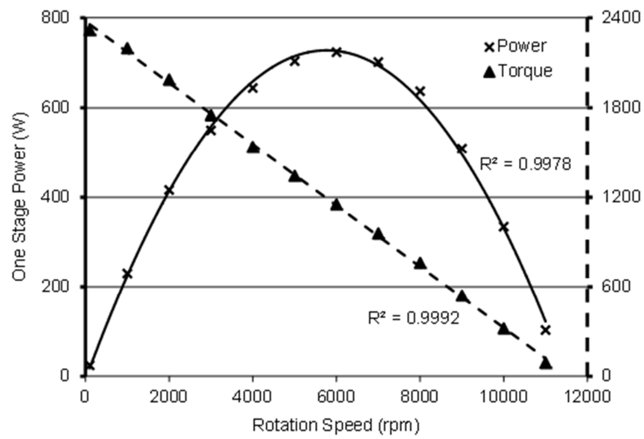

Figure 1 – CFD simulation results of power and torque versus rpm for one Stage turbodrill and water flow rate of 4 L/s.

Figure 2 shows the CFD simulation of the velocity profile at a rotation speed of 6,000 rpm which is close to the optimum rotation speed. The figure shows the velocity profile encircling the blades at the span surface, half way between the hub and the shroud. Some flow separations are visible on the leading and trailing edges of the blades.

Figure 2 also shows the pressure and meridional velocity profiles at the meridional surface. The meridional surface is the axial-symmetric surface between the hub and the shroud. The pressure and velocity profiles show that the maximum velocity and minimum pressure is occurring near the stator blade trailing edge. The simulation results in this study showed that the turbodrill performance is highly dependent on the flow rate of the drilling fluid. As the flow rate increases the expected rotation speed of the turbodrill and consequently the output power and torque will increase, (Mokaramian et al., 2013).

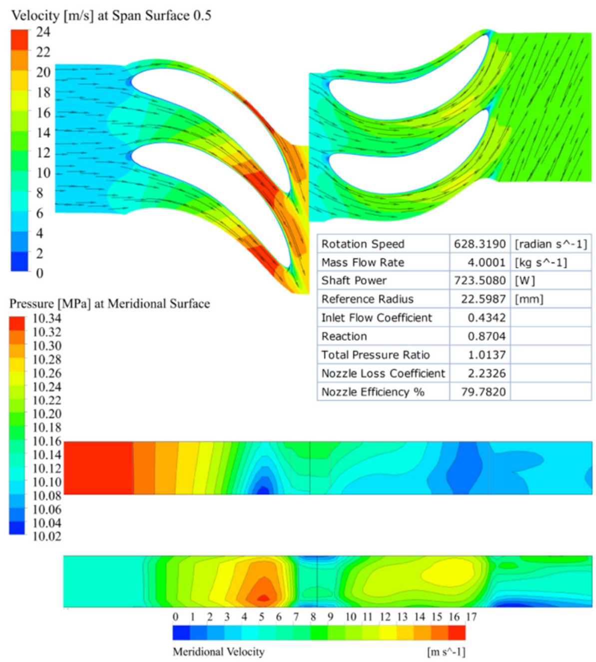

Figure 2 – CFD simulation results for one stage of the Turbodrill model with water flow rate of 4 L/s at 6,000 rpm rotation speed

FLOW LOOP DESIGN

The CT rig is mainly used by the oil and gas industry where the cuttings are transported to the surface and discarded. On the other hand, the application of CT for mineral exploration would require a careful cutting transport technique without losing any of the particles for proper logging and analysis. Cutting transport concerns of the petroleum industry are identified and addressed by Kamyab, Rasouli, Cavanough, and Mandal (2012), as well as the predicted issues of cutting transport in mineral exploration drilling. For mineral exploration, it is recommended to drill micro borehole sizes to achieve the objective of fast, cheap drilling and least environmental foot print. Micro borehole CT drilling was first introduced by the US Department of Energy for better reservoir imaging (Lang, 2006). A relative comparison between oil and gas and mineral exploration cutting transport operating conditions and criteria are presented in Table 1. For instance, the annulus space in mineral exploration drilling using CT is very narrow, compared to the larger annulus space in conventional oil and gas drilling operations. In addition, the down-hole turbo motor is expected to rotate the bit, therefore it requires a high flow rate of drilling fluid. The mud velocity is higher in the annulus space of the micro borehole CT drilling rig which in turn changes the flow regime to turbulent. Accordingly, it causes higher pressure loss during micro bore hole CT drilling than during conventional oil & gas drilling. Another difference is in the cuttings sizes. Since an impregnated diamond bit is used in drilling the mineral rocks, it generates micro-size cuttings. The last criterion compared is the unitless Stokes number which is used to identify how the particles follow and adapt themselves to the fluid stream in a slurry flow, according to equation (3):

$$St = \frac{\tau_p}{\tau_f}, \tau_p = \frac{\rho_p {d_p}^2}{18\mu}, \tau_f = \frac{L_s}{V_s} \Rightarrow St = \frac{\rho_p {d_p}^2}{18\mu}\frac{V_s}{L_s}. \tag{3}$$

where τ_p is the particles response time; τ_f is the Kolmogorov time scale defined as the ratio of the characteristic length (L_s) of a swirl to its characteristic velocity (V_s); ρ_p is particles density, d_p is particles diameter; and μ is fluid apparent viscosity. The Stokes number is unitless, thus the lower the value, the more the particles track fluid flow. The Stokes number for micro borehole CT drilling is smaller than for the petroleum cuttings transport. Therefore, the transportation of the particles in micro borehole CT drilling is easier.

Table 1 **–** Comparison between cutting transport for the oil & gas industry and micro-bore hole for the mining industry

Criteria	***Conventional Oil & Gas***	***Micro Bore Hole CT Drilling***
Annulus space	●	•
Velocity	•	●
Flow regime	laminar	Turbulent
Annular pressure loss	•	●
Cuttings size	●	•
Stokes number (order of magnitude)	1	10^{-3}

Rheology Effect and Flow Loop Design

Effect of Rheology

Experimental work indicated that hard rock drilling of small sized cuttings significantly affects the drilling mud rheological properties. Contrary to oil and gas drilling applications where large sized cuttings are produced, small sized cuttings have no effect on drilling slurry rheology and their effects can be neglected. Therefore the cuttings and mud mixture viscosity is assumed to be equal to the raw mud viscosity (Doron et al, 1987; Doron & Barnea, 1996; Naganawa & Nomura, 2006; Xiao-le et al, 2010). Experimental work has been performed to understand whether hard rock drilling will behave similar to oil and gas drilling operation. Three mud samples were prepared and their rheological properties were measured using a Fann V-G Viscometer. Cuttings with different concentrations were added to the original mud and their rheological properties were measured. The Herschel–Bulkley model was the best fit to the drilling mud rheology results. Later, a pressure loss model (Kelessidis, Dalamarinis et al. 2011) was used to show the significance of rheological changes. The results of one of the mud experiments are shown in

Figure **3**. The figure shows the effect of annular fluid velocity, cuttings concentration and annular clearance on the pressure loss. Increasing the flow velocity in the annulus space increased the pressure loss. As the cuttings concentration increased from 0 to 5% and 10%, pressure losses considerably increased. The cuttings concentration is ignored in conventional oil and gas applications. The annular clearance significantly affects the pressure loss, where the smaller the annulus clearance, the higher the pressure loss.

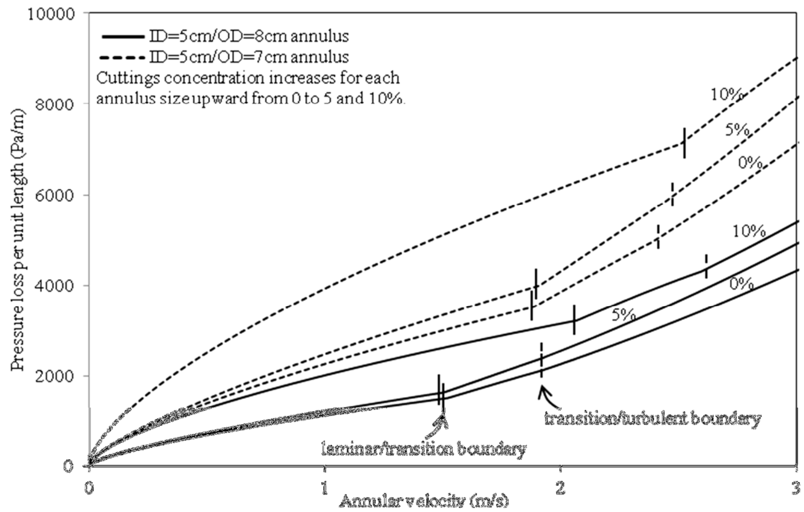

Figure 3 – Effect of annular velocity, cuttings concentration and annular clearance on the pressure loss in micro bore-hole CT drill

Experimental Work:

Lack of adequate knowledge in the area of cutting transport for hard rock drilling motivates this study to perform both numerical simulations and experimental work. Figure 4 shows a schematic diagram of a slurry loop that is proposed to be used for studying cutting transport in an annular space. The controlling variables in this design include: fluid properties such as mud type, density and rheological parameters; cutting concentration which is a function of the rate of penetration (ROP); cutting size; bore-hole angle which ranges from horizontal (180^{o}) and deviates (variable angles) to vertical (90^{o}); flow rate and annulus space size between the hole and inner pipe.

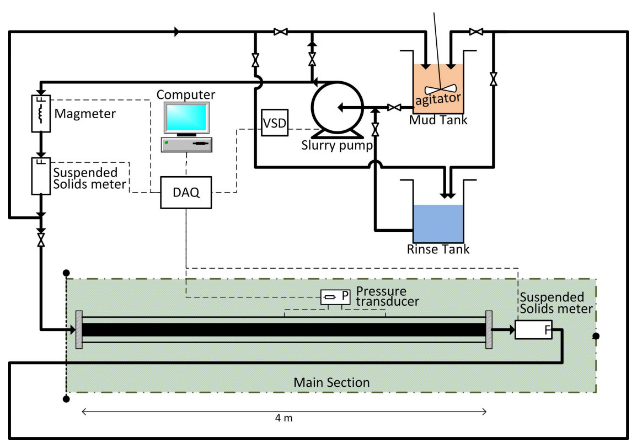

Figure 4 – Schematic of a proposed slurry loop for cuttings transport studies.

COILED TUBE MATERIAL

To achieve the objective of utilising the CT rig for mineral exploration, it requires the rig to be light in weight for safe and quick transportation to the drilling locations and needs to handle multiple bending events before failing due to fatigue. CT is exposed to multiple mechanical stresses as tension, compression, creep, fatigue, erosion and corrosion. The main cause of failure of the tube string is the multiple bending events of the tube. The CT is exposed to six different bending events during the drilling process, as illustrated

Figure 5.

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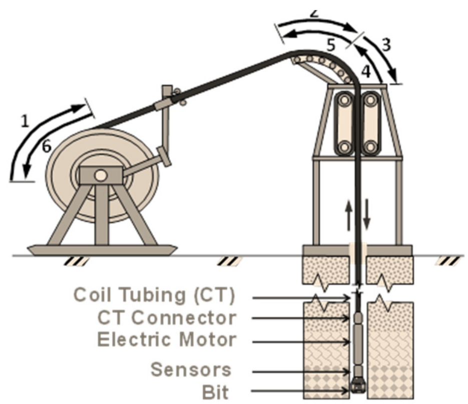

Figure 5 – Schematic of the CT bending events when running in and out of the wellbore, after Jaworsky and Williams (1993)

Three bend events occur while transporting the CT into the drill hole. One bend is wrapped around the reel, and then the tube is pulled off the reel by the injector head. The reel resists the pull of the tube, creating a tension load that straightens the bent tube. The second bend event occurs around the tubing guide. The tube is then pulled towards the injector head, where it is straightened, facing the ground to start the drilling process. When the drilling job is finished, similar three bend events occur in reverse. The six bend events are considered to be one industrial cycle, which is equivalent to drilling one hole. If a deviated angled drilling operation is required, that would add two more bend events to the drilling process.

During operation the CT is also exposed to internal pressure due to the drilling fluid. The bent section of the tube is exposed to triaxial stress, the internal pressure from the fluid, tensile stress and compressive stress at both sides of the tube circumference, as illustrated in

Figure 6. Stresses on the bent section of the tube, along with the internal pressure, exposes the tube to wall thinning and localised plastic deformation. The uneven deformation along the tube leads to burst failure. Jaworsky and Williams (1993) collected data from field testing and their empirical evaluation showed that, when the outer diameter of the tube increases by 3%, the wall thickness decreases by 7.5%, which leads to an increase of burst and collapse pressure rate by about 10%. Jaworsky and Williams (1993) added that yield strength of tubing samples, acquired from field services, decreased.

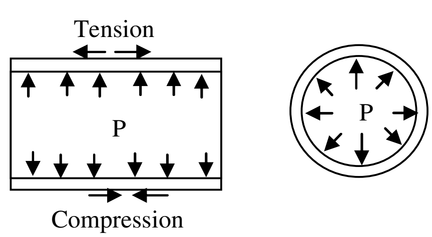

Figure 6 – Schematic diagram of stress distribution on CT

Material Selection Procedure

A performance index is utilised in this study to select the optimum material for the CT drilling string. The initial stage of material selection is to list all the requirements of the application and the equivalent material property that will satisfy such requirements. A list of possible candidate materials that will convey the requirements are chosen. Requirements can be categorised as rigid and soft. Rigid requirements are the ones for which no compromise is allowed, while the soft requirements are usually ignored in the selection process (Farag, 2007). Initial selection procedures are addressed by Ashby (1997) who developed materials selection charts based on performance indices of two rigid property requirements. Dargie, Parmeshwar, and Wilson (1982) compiled a mathematical model to assist in the initial selection procedure. Initial selection using rigid parameters is considered an elimination process rather than a selection process. Therefore, initial selection would lead to multiple possible candidate materials which all will execute the job. However, one of the candidate materials would be a better choice if the soft properties were quantitatively evaluated.

The performance index method is a practical quantitative method that can be used to evaluate the soft properties. The selection process is split into three main steps. The first step prioritises the material properties required to perform the job using the digital logic method and weighting factor. The second step evaluates the candidate materials and their properties relative to each other. The third and last step relates the required priorities to the candidate materials' properties as per the flow chart shown in Figure 7.

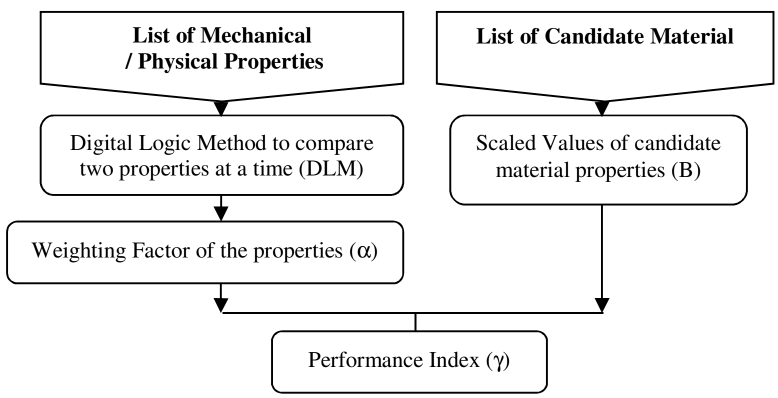

Figure 7 – Material selection flow chart

For CT selection, the rigid properties would be ductility and weight. The tubes need to be ductile to bend around the reel and light for safe mobility and fast productivity. The suggested materials would be any material excluding high strength brittle material such as high carbon steels or thermoset polymers or ceramics. Therefore, ranking the soft properties was essential to reach a quantitative and knowledgeable decision. A material selection analysis was carried out by Roufail and Rasouli (2012) on a variety of candidate material for CT rigs using the performance index method. The performance indices are evaluated based on the candidate materials' unit weight, bendability, load carrying capacity, specific stiffness, and fracture toughness and corrosion resistance. The candidate materials chosen for this analysis were two types of HSLA steel, GT90 and GT100, respectively, 63% carbon fibre, 56% E-class glass fibre, 73% e-class fibre and 6061 aluminium alloy. The results suggested that composite materials which are two glass fibres and carbon fibre would score the highest performance indices, these being 62.2, 51.4 and 48.2, respectively. The highest performance index value is scored by the 56% glass fibre composite.

Fatigue Testing Machine

The critical parameter which causes most of the catastrophic failures during drilling operation using CT is the fatigue endurance limit for bend loading. The second most important parameter is the weight of the rig, which is mostly dictated by the type of tube material. A bending fixture machine that will evaluate the fatigue bend strength of the available tubes is designed and manufactured as shown in Figure 8. The machine will pull the tube to a bent form with an adjustable radius of 40 - 70 inches. Then the tube is pushed back to a flat position using a hydraulic piston. The force required to bend the tube will be measured via a load cell, the number of cycles of bend/flat events will be logged, and the strain will be measured by means of an extensometer, which will be mounted on the outer diameter of the tube to measure local strain. Data will be recorded using a data acquisition system. Fatigued tubes can be further tested either using a non-destructive method for any initiation of cracks at intervals of bend events and/or will be evaluated for its possible mechanical properties deterioration using a tensile or burst test. Data collected from experimental work will be used as input to the material's performance index for material selection.

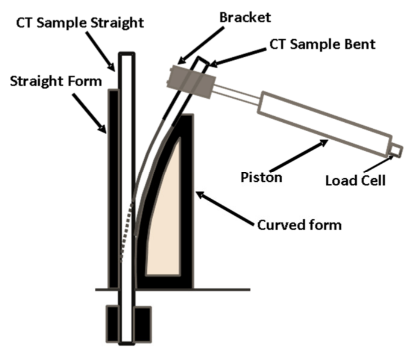

Figure 8 – Schematic diagram of the bending testing machine

CONCLUSIONS

Utilising a CT rig for mineral exploration requires drilling multiple micro boreholes and collection of the drilled rocks at the surface for mineral content analysis. The re-design of the rig is approached by considering three main components. The first component is the driving drilling power that achieves a high ROP; the second is the collection of the drilled particles to the surface for analysis; and the third is sustaining the drill rig string for multiple drilling events without failure as well as decreasing the overall weight of the rig for transportation and handling.

The first component is achieved by designing a turbo motor and was evaluated using finite element analysis (FEA), volume method (FVM) and CFD. This paper reported a few simulation results for small diameter turbo drill design optimization for minimum drilling fluid flow rate, while generating required power and speed. The motor is evaluated using water as a Newtonian fluid and non-Newtonian fluid as primary driving fluids. The fluid is used as a carrying fluid for the cuttings and as a cooling agent. The second phase is to manufacture a prototype of the motor for field testing.

The second component is the flow loop design which transports the cuttings to the surface for mineral composition analysis. Since CT rigs were originally used in the oil and gas industry, a comparison of the flow criteria between the application in the conventional oil and gas industry and the micro borehole for mineral exploration is made. Also the effect of the cutting mud type and the amount of cuttings (drilled particles) created during drilling on the fluid's rheological properties are analysed. The increase of the flow velocity as well as increasing the percent of cuttings and a small annular clearance resulted in considerable pressure loss increase. The increase of the pressure loss in the system decreases the carrying capacity of the fluid. The second phase in this study is to experimentally prove the theoretical findings using a proposed experimental set up for flow loop analysis. The flow loop will also study the effect of the angle of drilling on the carrying efficiency of the cuttings to the surface.

The third component is the choice of CT material that will perform the drilling operation multiple times without failing. The material that will be chosen needs to be light in weight to safely transport the rig to the drilling locations in a fast manner. A performance index method is suggested for material selection of the tube string. The rigid parameters assessed were ductility and weight. A theoretical selection model is performed and it was suggested that composite materials, either carbon or glass fibre, are the best choices. The highest performance index value was for the 56% fibre glass composite material. The different manufacturing techniques for composites, such as the number of fibre layers and their angles, will dictate the mechanical properties of the tube strings. Since fatigue is one of the most critical parameters that would cause failure during operation and shortens the life span of the tube, a fatigue testing machine is designed and manufactured to evaluate the fatigue endurance limits of the different pre-fabricated composite CT versus conventional steel tubes.

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