MODELING AND CFD SIMULATION OF A DAWNHOLE TURBINE MOTOR (TURBODRILL) IN DIRECTIONAL DRILLING

F.S. dos Santos, phelipe.moutinho@gmail.com
Institute Federal Education, Science and Technology of Amazonas (IFAM), Av. Sete de setembro, 1975, Manaus, Postal code: 69020 – 120, Brazil

J.S. Viana, jessicaviana.333@gmail.com
Federal University of Amazonas (UFAM), Av. General Rodrigo Octávio, Coroado I, 6200, Manaus, Postal code: 69077 – 000, Brazil

S.R.M. Sarkis, saviosarkis@yahoo.com.br
Federal University of Amazonas (UFAM), Av. General Rodrigo Octávio, Coroado I, 6200, Manaus, Postal code: 69077 – 000, Brazil

Abstract. *Turbodrill were the first downhole motors that found widespread application. The first turbines adopted commercially and tested for drilling in the USSR were conceived and designed by M.A. Kapelyushnikov in 1923–1932. Turbodrill is a type of hydraulic axial turbomachinery, which has a multistage blade consisting of stators and rotors. It converts the hydraulic power provided by the drilling fluid to mechanical power through turbine motor while diverting the fluid flow through the stator vanes to the rotor vanes. A turbodrill power section is entirely metallic (metallic turbine blades, metallic shaft, metallic housing, etc.), therefore, the tool is extremely resistant to high temperatures and high pressures. Historically, turbodrills have proven to be the most reliable drive mechanism in elevated temperature environments. In many cases, turbodrills are the exclusive drive mechanism used in high temperature/high pressure areas because of the tool's ability to reliably operate in extreme environments. Numerical simulations of a downhole turbine motor (Turbodrill) are presented which are optimised for Coiled Tube Turbodrilling in deep hard rocks mineral exploration applications. This paper presents computational fluid dynamics (CFD) simulations of a single stage turbodrill performance with different rotation speeds and mass flow rates. As a result optimum performance parameters are proposed for gaining the required rotation speed and torque for hard rocks drilling.*

Keywords*: Turbodrill, CFD, optimum performance.*

1. INTRODUCTION

In recent years, with the rapid development of economy, Brazil pay more attention to resources, energy security, stepped up environmental protection, clean energy exploration and development investment, the mineral resources and clean energy (such as natural gas, manganese etc.) despite the pre-salt discovery. Exploration workload will be increase.

Since the 1980s, downhole motors, especially the turbodrill and screw drill had been widely and rapidly applied. It has become an essential drilling tool for directional wells, cluster wells, horizontal wells and special process operations. Downhole motor, because of its superiority on the structure and the performance, it has played a significant role in not only promoting the mechanical drilling rate reducing the cost, but also ensuring the drilling quality and safety. The use of downhole motor can reduce the energy consumption caused by the friction between long drill string and borehole, and reduce drill pipe wear, (Mingxin et al, 2014).

In general, the downhole turbine motor is composed of two sections: turbine motor section and bearing section, i.e. thrust-bearing and radial support bearing (Eskin and Maurer, 1997). Fig. 1 shows a typical turbodrill assembly and the fluid flow path through turbine stages. The activating drilling mud or freshwater is pumped at high velocity through the motor section, which, because of the vane angle of each rotor and stator (one stage), causes the rotor to rotate the shaft of the motor which is connected to the bit. The energy required to change the rotational direction of the drilling fluid is transformed into rotational and axial (thrust) forces. This energy transfer is seen as a pressure drop in the drilling fluid. The thrust is typically absorbed by the thrust bearings. The rotational force causes the rotor to rotate relative to the housing. In practice, multiple stages are stacked coaxially until the desired power and torque is achieved, (Mokaramian et al, 2012).

Turbodrills obtain hydraulic power to rotate a drill bit from the flow of drilling fluids, (mud, foam, or air). This hydraulic flow is converted to rotary movement by a system of blades within the turbine assembly. They may be variable pressure profile blades or constant pressure drop blades. The efficiency of the turbine section rotor and stator blade is the effectiveness to convert hydraulic energy to mechanical energy in the form of rotation and torque at the bit. The Smith Neyrfor commercial turbodrill efficiency is 50% (United States Department of Energy, 2011).

With the advancement of oil exploration, the augment of drilling depth, and the increase of drilling difficulty, the relative well failure such as casing wear and drilling tool rupture has been keeping on increasing. The key to increasing the penetration rate of turbo-drilling is the selection of bit shape and the drilling parameters. It is an economical method to shorten the R&D cycle of turbine by applying the model software and CFD techniques into the analysis of velocity and pressure distribution of turbo-drilling flow field, instead of the fluid dynamic study of physical turbine type (Jianhong et al, 2011).

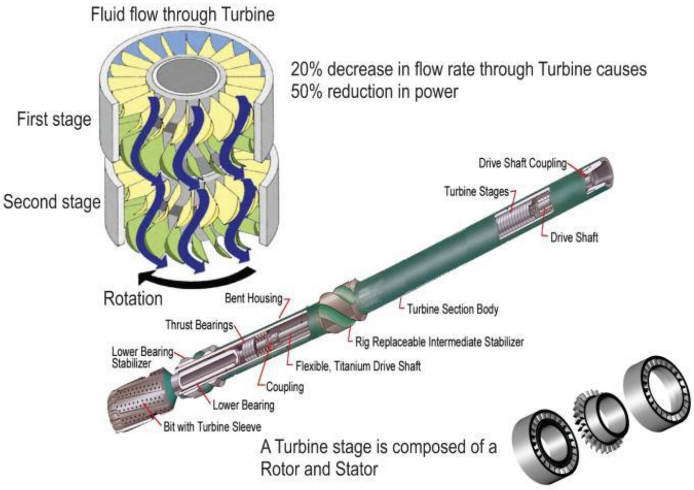

Figure 1. Turbodrill assembly and fluid flow through turbine stages, after (Beaton and Seale, 2004).

2. TURBODRILL DESIGN

The design of turbine energy characteristics for turbodrills is aimed at matching performance parameters with the torque and rotary speed required for the bit drive and its stabilization (Eskin and Maurer, 1997). When designing a hydraulic multistage turbine, it is assumed that each turbine stage is identical (i.e., that the flow rate, pressure drop, rotary speed, generated torque, when designing a hydraulic multistage turbine, it is assumed that each turbine stage is identical (i.e., that the flow rate, pressure drop, rotary speed, generated torque, and power transmitted to the shaft are the same for each of the stages) (Mokaramian et al, 2012). The well-known method of building velocity triangles (and polygons) is used when designing the blade unit profile (see Fig. 2). This method is useful for visualizing changes in the magnitude and direction of the fluid flow due to its interaction with the blade system. Fluid enters the stator with an absolute velocity c_1 and at an absolute velocity angle α_1 and accelerates to an absolute velocity c_2 at absolute velocity angle α_2. All angles are measured from the axial direction (x). From the velocity diagram, the rotor inlet relative velocity w_2, at a relative velocity angle β_2, is found by subtracting, vectorially, the blade speed, U, from the absolute velocity c_2. The relative flow within the rotor accelerates to relative velocity w_3 at an angle β_3 at rotor outlet. In this study, the analysis of the flow-field within the rotating blades of a turbodrill is performed in a frame of reference that is stationary relative to the blades. In this frame of reference, the flow appears as steady, whereas in the absolute frame of reference it would be unsteady. This makes any calculations significantly more straightforward and therefore relative velocities and relative flow quantities are used in this study (Mokaramian et al, 2013).

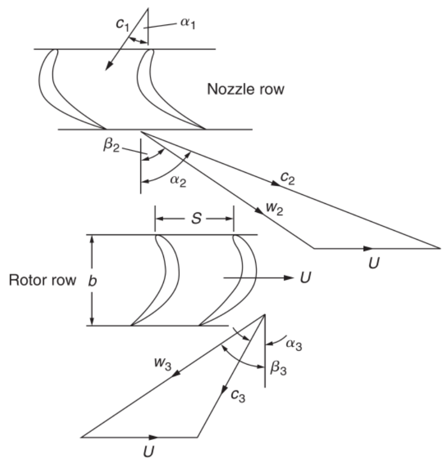

Figure 2. Turbine Stage Velocity Diagrams (Dixon and Hall, 2010).

Dr. Man Mohan Rai at the NASA Ames Research Center, Moffett Field, CA in 2011 has developed a series of fluid dynamic algorithms and neural networks which have been successfully used for redesign of turbine blades to optimum efficiency. Dr. Rai produced an improved blade design given the mechanical operating requirements and hydraulic flow conditions, both steady and unsteady flow. Additionally, since flow conditions change, it is possible to maintain near-optimal performance levels at otherwise off-design operating conditions. Additionally, the accuracy to which the optimal shape is manufactured depends on the manufacturing tolerances and normal wear and tear. These requirements lead to the need for a robust optimal design solution. Thus, evolutionary algorithms are needed, and the learning of the neural network is used to achieve robust optimal design solutions. Both traditional response surface methodology (RMS) and neural networks are incorporated in this design method by a strategy called parameter-based partitioning of the design space. Starting with the reference design, a sequence of turbine vane response surfaces based on both neural networks and polynomial fits are constructed to traverse the turbine vane profile in search of the optimal solution. Fig. 3 shown below is an illustration of computational fluid dynamics as it applies to the turbodrill. To our knowledge, this was the first use of these state-of-the-art techniques for petroleum turbodrills. Dr. Rai presented the results of his modelling and methodology while training Smith Neyrfor project personnel in the use of the system (United States Department of Energy, 2011).

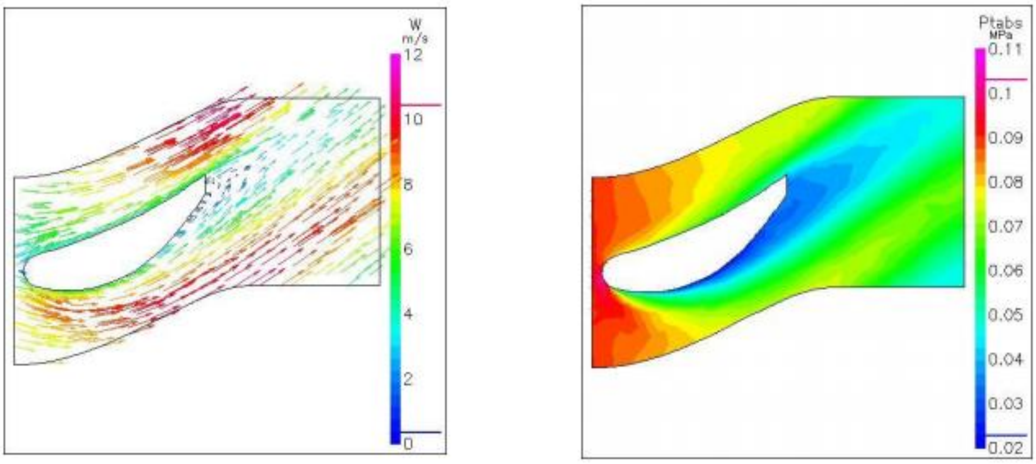

Figure 3. Computational Fluid Dynamics (United States Department of Energy, 2011).

3. HYDRODYNAMIC MODEL OF TURBODRILL TOLL

Recently Jianhong et al (2011) related that continuity equation is the equation of mass conservation that any liquidity issues must satisfy. The differential form of flow continuity equation in turbine is as followed:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_x)}{\partial x} + \frac{\partial(\rho u_y)}{\partial y} + \frac{\partial(\rho u_z)}{\partial z} = 0 \tag{1}$$

In equation (1), *ux*, *uy*, *uz* represent velocity components in x, y, z directions (m/s), t: time (s), ρ: density (*kg/cm*^{3}). The momentum equation in x, y, z directions are shown in equation (2), (3), (4) as Jianhong et al (2011).

$$\frac{\partial(\rho u_x)}{\partial t} + \nabla \bullet (\rho u_x u^p) = -\frac{\partial \rho}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \tag{2}$$

$$\frac{\partial(\rho u_y)}{\partial t} + \nabla \bullet (\rho u_y u^p) = -\frac{\partial \rho}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \tag{3}$$

$$\frac{\partial(\rho u_z)}{\partial t} + \nabla \bullet (\rho u_z u^p) = -\frac{\partial \rho}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \tag{4}$$

In equation (2), (3), (4), p is the fluid pressure of micro-element, (Pa), τ_{xx}, τ_{xy}, τ_{xz} are the components of viscous stress τ, caused by the molecular velocity effecting on the infinitesimal surface, (Pa), j_x, j_y, j_z represent the mass forces per unit in three directions, m/s^2, if the mass force is gravitated only and the axis of z is vertically upwards, then $j_x=j_y=0$， $j_z=-g$.

4. ANSYS BLADEGEN

ANSYS BladeGen is a geometry creation tool that is specialized for turbomachinery blades (ANSYS inc., 2013). BladeGen has its own documentation that can be accessed through the user interface, or by browsing the installation directory. The main documentation, “ANSYS BladeGen User's Guide”, is available from the Help menu in BladeGen.

4.1 ANSYS BladeEditor

According to ANSYS inc. (2013), ANSYS BladeEditor is a plugin for ANSYS DesignModeler for creating, importing, and editing blade geometry. Using BladeEditor, we can create a blade from scratch. We can also import a blade from ANSYS BladeGen. Once we have a blade in DesignModeler, we can use it as we would any geometry created in DesignModeler. In addition, we can use BladeEditor to export the geometry for use in ANSYS TurboGrid (a meshing tool) and Vista TF (a throughflow analysis tool).
BladeModeler requires an ANSYS license to use, although BladeGen will run in "demonstration" mode without the license (no saving or exporting is possible in this mode). Without the license the BladeGen system does not appear in the Toolbox, and the only way to access BladeGen is to open a previously saved project that contains a BladeGen system.
The BladeEditor user interface extends the DesignModeler user interface in the following ways:

- There are new feature types aimed at creating a blade and flow passage.
- There is a set of toolbar icons, most of which are used to create the new feature types.
- There are new views associated with some of the feature types.
- There are new context menu commands associated with the new views.

4.1.1 Flow Path Contour Creation

The main elements of a multi-blade row machine are the flow path and the individual blade rows, as shown in Fig. 4: Flow Path and Blade Row Concepts.

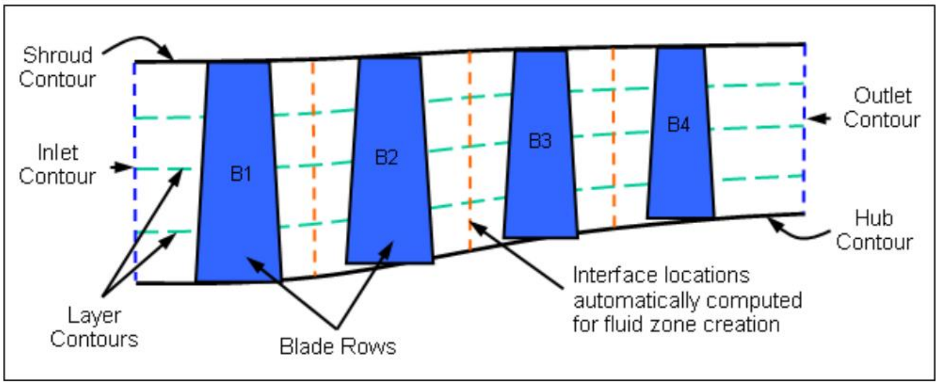

Figure 4. Flow Path and Blade Row Concepts (ANSYS inc, 2013).

The first step in creating new blade row geometry is creating the flow path contours that define the hub, shroud, inlet and outlet. The flow path contours are defined by sketch edges, which can be created using the existing DesignModeler sketch tools. Each contour (hub, shroud, etc.) should be defined in a separate sketch. This implicitly identifies all the edges belonging to a given contour. All contour sketches are expected to lie on the same Plane feature. Not only will this guarantee that the contours are coplanar, it will enable you to apply constraints and dimensions between sketches.
Contour sketches must be created on the (global) ZX-plane. The local X and Y axes on the sketch plane correspond to the global Z and X axes, respectively. The local X axis corresponds to the machine axis and the local Y axis corresponds to the radial coordinate axis. Consequently, all flow contours in the sketch must have positive Y coordinates. The hub, shroud, inlet, and outlet contour end points must be coincident.

4.2 Importing Blades from ANSYS BladeGen

BladeEditor provides a geometry connection between BladeGen and DesignModeler. Reasons for importing BladeGen blades into DesignModeler include:

- ANSYS BladeGen can output geometry in many different point data formats, but its surface output in IGES format is cumbersome to use.
- BladeGen does not produce a solid model in a standardized format such as Parasolid.
- We can combine an imported blade with other CAD geometry imported via one of the many DesignModeler-supported CAD file formats.

Through BladeEditor, one or more BladeGen models can be linked into a DesignModeler session, so that any changes to the BladeGen models will be reflected in DesignModeler the next time you update the Geometry cell. When we import a BladeGen model, BladeEditor does the following:

- Constructs blade surfaces.
- Creates a solid model for the blades and hub.
- Creates 2D sketches for the meridional contours and non-flow-path hub geometry.
- Creates periodic fluid zones.

The preferred method of importing a BladeGen file is to create a link from the Blade Design cell of a BladeGen system to the Geometry cell. This link maintains the data transfer relationship between the two cells. The desired import options should be set in the Blade Design cell properties.

5. PARAMETERS

Tab. 1 show the commercial turbine parameters (TPM3-195 and TP-178) obtained of Eskin and Maurer (1997). These values were adopted to realize the simulations in ANSYS FLUENT with 250 iterations and the turbodrill design was done in ANSYS BLADEGEN using the constituent parameters of TPM3 - 195 and TP - 178. The work fluid used was water, the mass flow rate was 28 l/s, temperature of 120°C, pressure diference of 2.4 MPa to 3.8 MPa for TPM3 – 195 and 6.1 MPa to 8.8 MPa for TP - 178. The simulate conditions were based in works of Yu et al (2014), Mokaramian et al (2012, 2013) and Roufail et al (2012).

Table 1. Constituent data for turbodrill (adapted of Eskin and Maurer, 1997)

Property	TPM3-195	TP-178
Number of Turbine Stages	40	40
Blade Shroud (mm)	4	4
Blade Thickness (mm)	1	1
Drilling Mud Flow Rate (l/s)	24 to 30	24 to 28
Inlet Angle	60°	60°
Pressure Difference (Mpa)	2.4 to 3.8	6.1 to 8.8
Rotation Type	Positive	Positive
Rotatory Frequency (rpm)	120	120
Torque (N.m)	4000 to 5000	3000 to 4000
Turbine Lenght (m)	5.9	8.6

6. RESULTS

After simulations the results were compared with current literature. Figure 5 show the turbine meshes for TPM-195, where the meshes near the blade are relatively uniform. This prove that the mesh quality is high. Fig. 6 the internal structure of the turbodrill, figure 7 and 8 show the results of temperature simulation for turbine blade TPM3 – 195 and TP – 178 where we can observe the expansion linear effects, fig. 9 and 10 the turbine blade pressure simulation for TPM3 – 195 and TP – 178 where pressure distribution is better observed in TPM3 – 15. Was observed that 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).

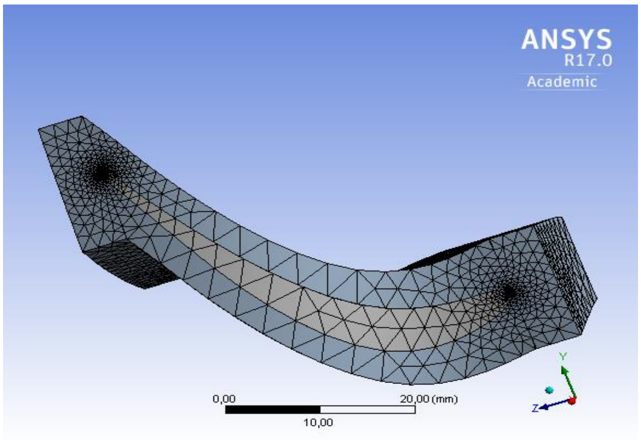

Figure 5. Turbodrill internal structure

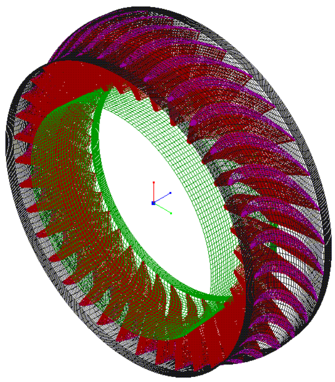

Figure 6. Profile of blade mesh

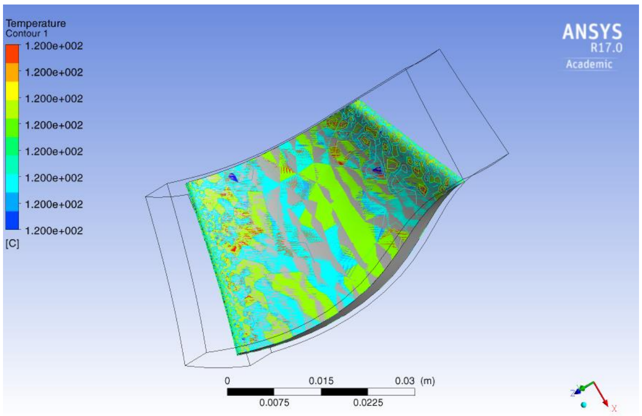

Figure 7. Temperature profile of turbodrill blade TPM3 - 195

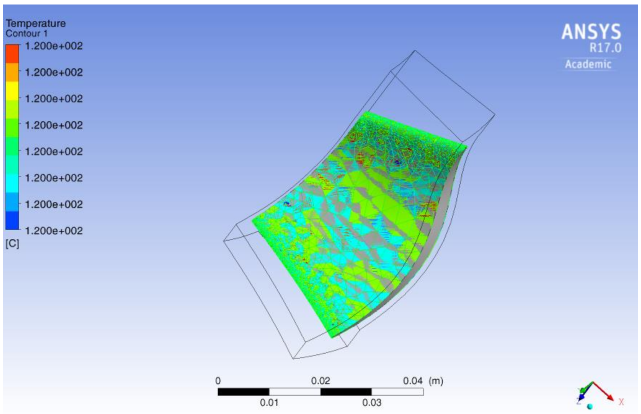

Figure 8. Temperature profile of turbodrill blade TP - 178

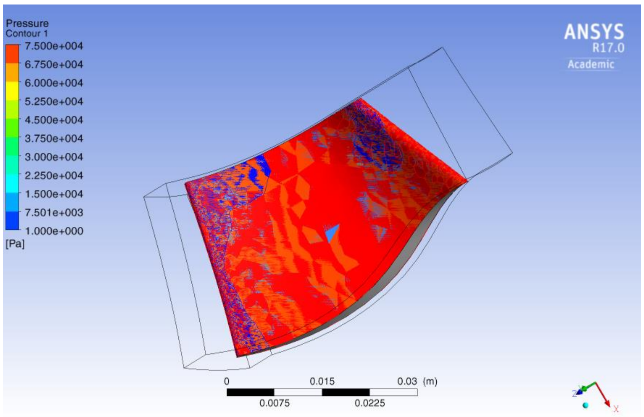

Figure 9. Pressure profile of turbodrill blade TPM3 - 195

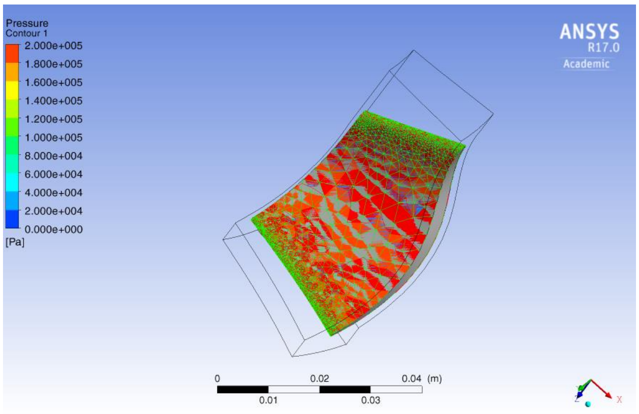

Figure 10. Pressure profile of turbodrill blade TP - 178

The simulate result in this paper showed that dependence of the turbodrill performance in relation on flow rate of the drilling fluid. The results of the analyses structural of mechanical stress showed that the maximum stress occurred near to the trailing edge of the stator blades in agreement with results of Mokaramian et al (2013).

7. CONCLUSIONS

A 3-D modelling of the turbodrill was set-up and the numerical simulations showed that the adjustment of flow parameters, such as drilling fluid density, discharge and viscosity improve the hydraulic efficiency of turbo-drilling tools. The obtained results corroborate with the literature, blade profile suffers stress in the inlet flow rate and the right select of the material for turbodrill blade manufacturing is fundamental to get good results during the drilling and extending the useful life of the tool. Was also noticed that increase in the flow rate during the drilling affect the turbodrill performance, more studies are needed to obtain better conclusions about this influence.

8. ACKNOWLEDGEMENTS

At institutions IFAM, UFAM and to everyone who collaborate directly and indirectly for the project.

9. REFERENCES

ANSYS, inc., 2013. “ANSYS TurboSystem User's Guide”. ANSYS, Inc. is certified to ISO 9001:2008. Southpointe 275 Technology Drive Canonsburg, PA 15317 Canonsburg, ansysinfo@ansys.com; http://www.ansys.com . Release 15.0, November 2013.

Beaton, T. and Seale R., 2004. "The Use of Turbodrills in Coiled Tubing Applications". SPE/ICoTA Coiled Tubing Conference (SPE 89434), Houston, Texas, U.S.A.

Dixon, S.L. and Hall C.A., 2010. "Fluid Mechanics and Thermodynamics of Turbomachinery". The United States of America, Elsevier Inc.

Eskin, M. and Maurer W.C., 1997. "Advanced Downhole Drilling Motors", Maurer Engineering Inc.

Jianhong, F., Kexiong, S., Zhao, Z., Zhiqiang, Z., Dezhi, Z., Fei, L., Xin, Z., 2011. “Analysis on Three-Dimensional Numerical Simulation of Turbine Flow Characteristics”. In International Conference on Future Energy, Environment, and Materials. Energy Procedia 16, pp. 1259 – 1263.

Mingxin, H., Yu, W., Baolin, L., Mingshuai, G. and Liguang, W., 2014. “Development of Downhole Motor Drilling Test Platform”. In Geological Engineering Drilling Technology Conference (IGEDTC), New International Convention Exposition Center Chengdu Century City on 23rd-25th May 2014. Doi: 10.1016/j.proeng.2014.06.172, pp. 71 – 77.

Mokaramian, A., Rasouli, V. and Cavanough, G., 2012. “CFD Simulations of Turbodrill Performance with Asymmetric Stator and Rotor Blades Configuration”. In Ninth International Conference on CFD in the Minerals and Process Industries CSIRO, Melbourne, Australia 10-12 December 2012.

Mokaramian, A., Rasouli, V. and Cavanough, G., 2013. "Fluid Flow Investigation through Small Turbodrill for Optimal Performance". Mechanical Engineering Research; Vol. 3, N°. 1; 2013 ISSN 1927-0607 E-ISSN 1927-0615. Published by Canadian Center of Science and Education. Doi: 10.5539/mer.v3n1p1, pp. 1 – 24.

Roufail, R., Rasouli, V., Mokaramian, A., Kamyab, M., Lagat, C. and Cavanough, G., 2012. "UTILIZING COILED TUBE RIG FOR MINERAL EXPLORATION APPLICATION". Deep Exploration Technologies Cooperative Research Centre (DET CRC). DET-CRC document 2012/073, pp. 1 – 13.

United States Department of Energy, 2011. "Final Report: HIGH-POWER TURBODRILL AND DRILL BIT FOR DRILLING WITH COILED TUBING". DOE Award N°.: DE-FC26-06NT15486 Reporting Period: October 2004 to June 2008. Office of Fossil Energy, July 2011.

Yu,W, Jianyi, Y. and Zhijun, L., 2014. "Design and Development of Turbodrill Blade Used in Crystallized Section". Hindawi Publishing Corporation, The Scientific World Journal Volume 2014, Article ID 682963, http://dx.doi.org/10.1155/2014/682963, pp. 1 – 12.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.