Department of Energy National Petroleum Technology Office

Final Report

Work Performed Under Contract Task 03NT30429
Sub-Task 2:
Hydraulic Motion & Fluid Movement Through
Small Diameter Pipes and Wellbores
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1.0 Introduction

The purpose of this document is to identify information regarding hydraulic motion and fluid dynamics through small diameter pipes and well-bores. Of particular interest will be tubing diameters ranging from 3.00" to approximately 1.00" with specific application for Coil Tubing Drilling (CTD). As a result of this requirement, an extensive literature search was conducted that included, but not limited to, academic research, professional and technical papers, patents, professional periodicals, government research projects and technical manuals from coil tubing manufacturers. The scope of this document will include any available information specific to technologies associated with the dynamics of fluid motion during drilling and production operations. As a result of this statement, the formation and conclusion of this document will specifically pertain to critical factors regarding the drilling process and the subsequent production rates from various coiled tubing diameters if available. The data will include critical factors of fluid behavior, any available simulations and a general understanding of fluid flow in the process of CTD.

In order to successfully address these requirements, it is necessary to qualify certain aspects of this paper that include: the formation and approach to the topic of fluid dynamics as they relate to coil tubing drilling, the current data that is available on the subject, and provide a summary conclusion to data that was found.

The formation and approach to the literature search was conducted using various search criteria too numerous and cumbersome to categorize within this document. However, the results of the search criterion were isolated to several specific organizations based on the subject matter as it pertains to this document. Specifically, this includes research from the Society of Petroleum Engineers (SPE), academia, technical papers and manuals from industry and previous government research on related topics.

CTD, as with any relatively new technology, will experience an evolution based on the necessity to successfully implement and gain industry acceptance for the new technology. In the early years of CTD, a host of mechanical and process problems resulted in less than acceptable results. However, due to the persistence of industry leaders, academic researchers, coil tubing manufacturers and many other entities who worked collectively to solve many of these mechanical and process problems, there still remain several areas within CTD where the evolution must continue.

One of these critical areas happens to be the specific topic for this document which is fluid dynamics and fluid motion. Fluid dynamics is one of the most important factors regarding success or failure in coil tubing drilling as well as the subsequent production of oil and gas. As related to the drilling operation, fluids of varying viscosity and lubricity properties are pumped into the coil-tubing to the down-hole drill motor with surface pumps operating at various pressures depending on the drilling requirements and system limitation. These same fluids are also responsible for the transport of the drill cuttings to the surface thus completing the intake and return loop of the process drilling fluids. Although this is a simplistic analogy of what actually occurs, the complexity of the fluid motion in this process is critical in determining success, failure, efficiency and cost effectiveness of the process. Conversely, the ability to model, analyze and characterize the drilling and formation of the wellbore is also critical in the decision making process and the subsequent economic impact of the process.

Subsequent to the drilling and well preparation, the coil tubing becomes a transport medium for oil and gas from the well. At the present time, our research has not indicated a host of information regarding modeling, testing or analysis on coil tubing diameters much less than 3.00" primarily due to the reasoning that diameters less than 3.00" have not been considered by industry to be an effective method for delivering the product rate commonly utilized in industry. Although this theory is true regarding tubing diameter and production rates, tubing of smaller diameter could provide a significant increase in production rates of older wells or shallow wells, exploration and sensor deployment to the depth of approximately 5,000 feet with a significant reduction in energy requirements, transportation and set-up cost, overall footprint of the rig and time to complete. This assumes that proper design and implementation of surface equipment and conditions have been incorporated in the rig/well design. Subsequent to this literature search, it appears that little research regarding tubing sizes below 3.00" with respect to fluid dynamics, drilling and production has been conducted or published. Furthermore, at the present time, it is not fully recognized that an adequate code exists that can properly model, analyze and characterize fluid rheology or other dynamic flow requirements with any degree of confidence.

2.0 Results and Findings

The following identifies professional papers related to fluid dynamics and coil tubing drilling. However, the literature search did not reveal significant data regarding production rates on the targeted tubing diameters for this paper. The data was included to give the client a background in the type of research that has been conducted and future targeted areas for the modeling and analysis. The research has not identified significant data regarding production rates on coil tubing in the smaller size range. Furthermore, it is not apparent at this time that there are any immediate plans to research or analyze the fluid dynamics in the smaller tubing diameters for potential use as a viable production method. It is possible that research is currently being conducted on the smaller tubing diameters but the results have not been published or could be available from a source other than utilized in this document. However, various subject matter experts have concluded that it is unlikely and more research is needed in the smaller diameter tubing.

One of the most prominent leaders in technology development for the micro-drilling process is Los Alamos National Laboratory (LANL). Previous research conducted by LANL is summarized in a comprehensive and widely accepted document titled, "Road Map for a 5000-Ft Micro-Bore-Hole." This paper is a comprehensive, technically oriented study of micro-drilling that includes drilling, monitoring and production process capabilities. The paper further describes five critical areas that need to be developed for future implementation and five less critical that need to be developed. These issues will be discussed later in this paper; however, it should be noted at this point that one of the areas described for needed technology development is hydraulic circulation modeling.

Subsequent to completing this literature search, there are significant reason to believe that a comprehensive study should be conducted to determine both drilling and production efficiencies of tubing in the range of 3.00" to 1.00" diameter. Furthermore evidence of this need will be presented later in this document. The research conducted by RIO Technical Services, Inc. has identified the following resources that include both drilling and sparsely populated production information.

The following list identifies the subject of the paper, the author(s) and a brief summary of the paper's topic.

2.1 Significant Parameters Affecting Efficient Cuttings Transport In Horizontal and Deviated Well-Bores In Coil Tubing Drilling: A Critical Review

Authors: V.C Kelessidis, G. Mpandelis, A. Koutroulis and T. Michalakis. (Representatives of the Technical University of Crete, Greece) Paper presented at the 1st International Symposium of the Faculty of Mines (ITU) on Earth Sciences and Engineering, May 16-18, 2002, Maslak, Istanbul, Turkey.

Summary

Critical parameters are identified with regarding to fluid dynamics in cutting transports when drilling both horizontal and deviated well geometries. Many of the problems encountered with this type of drilling have been successfully addressed in conventional drilling, but a renewed interest has been established with coil tubing drilling primarily due to the cutting transport problems in horizontal and highly inclined annular geometries without rotation of the inner pipe. Among the critical factors to consider when effectively initiating proper cutting transport methodology include pump rates, well dimension, fluid properties, the size of cutting solids and the solids loading. Of particular interest in this paper is the section on three layer modeling. It is commonly known within the research disciplines that inadequacies exist in properly predicting two layer, fluid flow annulus models when compared to extending the two layer model to a three layer model. The purpose for extending data to a three layer model is to allow the prediction to include a moving bed on top of the stationary bed of solids. This provides two mass balance equations for solids and liquids and three momentum equations that include one for each layer, the suspension of heterogeneous solid–liquid layer, the moving bed and the stationary bed. However, as documented in the conclusion section of the paper, there is additional work that needs to be concluded to "establish the best rheology models for liquids, two versus three parameter models given the added complexity of three parameter models and the subsequent results are still questionable". Furthermore, if a continued effort to reduce the diameter of coil tubing for drilling and production is initiated, it is imperative that these models consider the smaller diameters. Having said this, it assumed the complexity of the models or the results of the analysis could provide additional data that would identify the effectiveness of smaller coil-tubing applications for drilling and production or identify the limitations, if any, for the proper deployment for a specific tubing diameter range.

Critical factors are listed in this paper regarding the effects of various parameters on efficient cuttings transport in concentric and eccentric annuli. The critical factors from this research are listed as follows:

- The most significant parameter in cuttings transport is the annulus mixture velocity (flow rate and cross sectional area).
- Flow should be turbulent in the annuli.
- Maximum flow rates should conform to maximum rates imposed by the down hole motor and maximum allowable pressure for the Coil tubing.
- Liquid density is an important parameter (increase in buoyancy for higher ρ).
- Eccentricity plays a significant role with a dramatic decrease in cuttings transport efficiency for fully eccentric annulus.

From published results and models to date, the primary issues regarding efficient cuttings transport are listed in the summary as follows:

- There is a need for good quality data, for both concentric and eccentric annulus with conditions similar (dynamic similarity) to the ones encountered in the field.
- There is a need to establish theoretically, the observed link (in the field and experiments) between fluid rheology and efficient cuttings transport.
- There is a need to establish the best rheological models for liquids, two versus three parameter models, given the added complexity of three parameter models and subsequent results are still questionable.
- There is a need to resolve the contradiction for using low viscosity fluids versus moderate viscosity fluids where results show better suspension characteristics for the latter but the former promotes turbulent flow.
- There is a need for better understanding regarding the solids distribution in the suspension layer; the dispersion coefficients of solids are very critical and better predictions are needed.
- There is a need to define the methodology regarding the question, "should the approach be the determination of minimum suspension velocity or the modeling of layers for efficient cuttings transport"?

For the modeling of minimum suspension velocities, the needs are:

- To find a relationship to link the turbulent fluctuating velocity component to the main flow parameters for annulus and non-Newtonian flows.
- To get better relationships for hindered settling of solids in non-Newtonian fluids
- To examine the effects of the presence of solids on the turbulent fluctuating velocity for non-Newtonian liquids.
- To compare predictions with good quality data.

For the layering modeling approach, the needs are:

- To justify the use of three layers (more complex) vs. the two layer model with good quality data.
- To make better predictions of the solids dispersion coefficient, *D*, hence determination of *Pe*.
- To validate the diffusion equation for the annulus.
- To provide a better closure relationships
    - for interfacial friction factor between heterogeneous layer and moving or stationary bed
    - for the wall friction factors for the heterogeneous layer and for the moving, valid for non Newtonian fluids.

2.2 Flow-Pattern Transition and Hydrodynamic Modeling of Churn Flow:

Authors: J.O. Tengesdal, SPE, Pennsylvania State University; A.S. Kaya, SPE, University of Tulsa; Cem Sarica, SPE, Pennsylvania Stat University. (SPE Journal 4 (4), December 1999)

Summary

The research team provides a thorough review of existing transition models specifically for slug-churn transitions and provides a new transition model based on the drift flux approach with experimental data. Traditionally, there are four basic flow patterns in a two-phase, gas-liquid flow in vertical and deviated pipe. The flow patterns are identified as bubble, slug, churn and annular flows. This research provides the following definition for the listed flows. “Slug flow consists of a series of unit cells, consisting of a gas pocket called a Taylor bubble, a plug of liquid called a liquid slug and a film of liquid around the Taylor bubble that is flowing downward. Churn flow is a chaotic flow pattern consisting of Taylor bubbles and liquid slugs that are distorted in shape. No continuity of the phases appears to be present because the slug is repeatedly destroyed by very high local gas concentration and/or the Taylor bubble collapses due to high liquid concentrations”. These flow patterns can dramatically influence the flow regime, delivery efficiency and pressure requirements. Additionally, the above named flow patterns have theoretical transition models or mechanisms to transition from one flow pattern to another. The available literature includes four major mechanisms for transition that were proposed and include; entrance effect, flooding, wake effect and bubble coalescence. Further definition of these mechanisms can be found in the paper and are intentionally omitted due to the scope of this document. However, the basis for the analysis and models specifically deals with flow transition in a 25.4mm or 1.00 inch tubing and provides enough data to understand that additional characterization of smaller diameter tubing is required particularly when 1.00” tubing is recommended for production at depths of 5,000 feet.

2.3 A Comprehensive Mechanistic Model for Upward Two-Phase Flow in Wellbores:

Authors: A.M. Ansari, Pakistan Petroleum Ltd.; N.D Sylvester, University Of Akron; C Sarcia, O. Shoham and J.P. Brill all from the University of Tulsa.

Summary

The goal of this research team was to formulate a detailed comprehensive mechanistic model for upward two-phase flow very similar in approach to the previous paper. It describes four distinct flow patterns that include bubble, slug, churn and annular flow; however, it provides results in a broader range of pipe diameters from 1.00 inch up to 8.00 inch. Furthermore, each transition model is evaluated against a wide range of experimental and field data made available from the updated Tulsa University Fluid Flow Projects (TUFFP) well data banks. The models are evaluated with six empherical correlations and one mechanistic model used in the field. Due to the similarity of this paper with respect to the previous paper, "*Flow-Pattern Transition and Hydrodynamic Modeling of Churn Flow,"* a detail summary will not be presented at this time. It is important to realize, however, that paper does include smaller diameter pipe within the range of interest. The paper also states, "due to the lack of published studies on comprehensive mechanistic models that relate to the various fluid flow patterns, more work is needed to develop models that describe the physical phenomena more rigorously".

2.4 Characterization of Oil-Water Flow Patterns in Vertical and Deviated Wells:

Authors: Jose G. Flores, Schlumberger Wireline & Testing, X. Tom Chen, Cem Sarica and James P. Brill all from the University of Tulsa. (Source SPE Paper 38810)

Summary

The contents of this research are not unlike the previous research papers listed above with regard to two-phase flow. However, the authors provide a unique approach with regard to several issues that include;

- This research deals specifically with oil-water flows from both a water dominated flow pattern as well as an oil dominated flow pattern.
- The tests were conducted with pipe angles of 90°, 75°, 60° and 45° in a transparent, 2.00" diameter pipe 51 feet long.
- Instrumentation for the experimental system included sensors to measure flow patterns, pressure drop, average hold up and spatial phase distribution, in addition to monitoring and controlling parameters such as mass flow rates, fluid densities, pressure, temperature and pipe inclination angles.
- This research was completed by utilizing both theoretical and experimental data with pipe diameters in the targeted range of interest.

The seven definitive conclusions listed in this paper specifically identify key issues in classification and characterization of oil-water flow patterns. Again, similar but in content and approach, there is a broader range of pipe sizes used for the experiment. However, due to the nature of the experimental study and the use of a transparent polymer base tubing, certain aspect such as frictional coefficients may not be representative of actual conditions. It is worth noting, however and as documented in the paper, "Inherent to each flow patterns are characteristic spatial distributions of the interface, flow mechanisms and distinct values for design parameters such as pressure gradient, hold-up and heat transfer coefficient" that are important to consider. Again, without duplicating additional information that has already been presented, it will be sufficient to mention only that the data presented in this summary, as well as the research documentation, is similar in nature to that already presented. However, the result of this experiment provides additional information and experimental approach not necessarily utilized in the other test set-ups.

2.5 An Experimental Study of Drag Reduction of Polymer Solutions in Coiled Tubing

Authors: Subash N. Shan, SPE and Y. Zhou, SPE Mewbourne School of Petroleum & Engineering, University of Oklahoma.

Summary

The data compiled in this research is distinctly different than the previous summaries that were presented in so much as it deals specifically with frictional losses in Coil Tubing (CT). Current experimental data has revealed higher frictional losses in CT as opposed to straight walled pipe. The frictional losses are even greater when associated with a radius of curvature and is believed to cause a secondary flow within the tubing. The data was established through experimental processes conducted at a sophisticated, full scale CT facility in a joint industry-university research effort. The experiment included multiple reels of CT in diameters that included 1.00", 1.500" and 2.375", fluid mixing and pumping systems and a data acquisition system to gather targeted information. Furthermore, there is a distinct difference in this data; specifically the results were to define the losses based on fluid injection into the well during the process of drilling and completing the well.

Fluids that were used in the experiment include water and solutions of polymers currently used in the well drilling and completion industries. Other materials include Xanthan gum, partially hydrolyzed polyacrylamide (PHPA), guar gum and hydroxyethylcellulose (HEC). As expected, the results of the data indicated that frictional drag reduction differs significantly among the different types of polymers and at different concentration levels. Additionally, the data interpretation and analysis revealed that additional effects on drag or frictional losses are directly related to the coil tubing diameter and the coil tubing-to-reel drum diameter ratios. The importance of this data was realized for not just the intended purpose of reducing friction, increasing the injection rate and reducing pumping cost, it is also significant in terms of the potential use of CT in a production environment which speaks directly to the purpose of this document. Frictional losses are realized both from an injection process of positive pressure or a pumping process with a negative pressure or suction. Therefore, based on the information contained in this document, it is critical to determine fluid viscosity, composition of the various fluid flow density patterns, energy cost, pumping requirements and system limitation prior to implementing CT as possible production mechanism. This in turn will require additional research.

2.6 Productivity and Injectivity of Horizontal Wells:

Author: Khalid Aziz, Stanford University, 1999. (Study completed under DOE Grant Number DE-FG22-93BC14862)

Summary

The primary goal of this research is to address pressure drop in long horizontal wells and the subsequent influence on well performance. The experimental methodology includes various aspects and conditions that apply in horizontal wells that could also be applied to directional drilling with coil tubing. One limiting factor is the test diameter of the tubing which was 6.125" at 100 feet in length. Although the diameter of the pipe is outside the targeted diameter for which we are seeking, the experimental methodology and test set up would apply to research directed to evaluating the same parameters to determine the potential for smaller diameter CT. Specifically, a test set-up could be established using various lengths, diameters and radii of coil tubing to determine experimentally parameters such as frictional loss, mass flow, velocity, pump pressure and flow patterns. Furthermore, the test could be conducted with fluids of various viscosity and density. The test configuration of this document could be used as a model for future testing and perhaps more sensors could be incorporated for gathering additional information. An experimental set-up of this nature could also be used to validate specific parameters of an analysis or code. The data from this research was included in this document simply as a resource or a fundamental model for any future fluid flow analysis using smaller diameter coil tubing.

2.7 Maximizing Gas Recovery in Slimhole wellbores Utilizing Coiled Tubing Pumping System (CTPS):

Authors: Michael Waid, Anadarko Petroleum; Humberto Leniek, Coil Tubing Americas; Stephen Rowland, BJ Services

Summary

Due to the many years of oil and gas production, a significant number of wells have reached production maturity with typical depletion rates of 80% or more. The petroleum industries recognize that additional quantities of hydrocarbons could still be extracted if advanced technologies existed that would enable industry to maximize recovery in a cost effective manner. This research was included as potential source regarding new technology applied to coil tubing and slimhole wellbores. Specifically those with 2.875" casing cemented in as the production string. In order to maximize recovery on older wells, coiled tubing pumping systems (CTPS's) are now being installed in slimhole wells to pump off the fluids in these wellbores. The first successful installation of a CTPS was developed to de-water a slimhole gas well which was completed by Anadarko Petroleum Corporation in October 2002 in the Carthage Field of east Texas.

The CTPS can be described as "similar in design to a standard rod pumping system with the exception being the coiled tubing string is both the rod string and the tubing string. The pump is anchored in the well and the coil tubing is attached to the pump with a weld or crimp on connector. The coil tubing string then travels all the way to the surface where it is then connected to the rod pump and the coil tubing physically is raised and lowered with each stroke of the pumping unit. A flexible connection at the surface then transfers fluid from the coil tubing string into the surface line".

"This technology was first initiated in South America in May 1998 with less than favorable results due to mechanical failures and was eventually abandoned. However, as with any new technology, refinements are made, problems are addressed and the technology soon evolves as is the case with the current CTPS configuration that was successfully deployed by Anadarko Petroleum Corporation in the Carthage Field of East Texas."

In order to achieve the success in East Texas, several design modification were necessary to overcome the mis-match with the anchoring system and Bottom Hole Assembly (BHA) in order to incorporate the CTPS. Specifically, this paper defines the necessary modifications to the anchoring system and the remaining components of the BHA. However, due to the length and complexity of the modification as well as the intended scope of this document, a detailed description of the modification will not be included at this point.

This system was installed on the subject well on October 8th, 2002. The six month production average of the well prior to the installation was 315mcfd. Subsequent to the installation and start-up, the well cleaned up and peaked at 550mcfd. Over a three month recording period the well averaged 470mcfd with the CTPS, experienced zero downtime hours and will continued to be monitored over the course of the implementation. The installation cost for the CTPS including all well work and surface equipment totaled $88,000.00. Again, an evolution is occurring with the anchoring system as a result of this installation. The evolution pertains to the anchoring system which, subsequent to the modification, will reduce the project cost by approximately $20,000.00. In order for CT to become widely accepted for industry use, technology such as described in this paper must be explored and brought to maturity.

2.8 Road Map For A 5000-FT Micro Bore Hole:

Authors: Jim Albright, Don Dreesen and Jim Blacic, Los Alamos National Laboratory (LANL); Jim Thompson, Lithos Associates; Tom Fairbanks, Nambe Geophysical, Inc.

Summary

The LANL research report is a comprehensive report on micro-drilling with respect to tubing diameters from 2-3/8" to 1-3/8" and mentions the potential for 1.175" tubing for production as well. The majority of the data provided has culminated from actual field test in which LANL developed a basic micro drilling rig to advance the micro-drilling concept with coil tubing demonstrations of 1-3/4" and 2-3/8" to a depth of 700 feet. However, in order to advance micro-drilling for commercial use, the process must be capable of economically reaching a depth of 5,000 feet in order to achieve production in shallow to medium depth wells or low productivity reservoirs. However, there is a section in this document that provides feedback from industry regarding acceptance of the micro-bore-hole which, as noted, is questionable at this point.

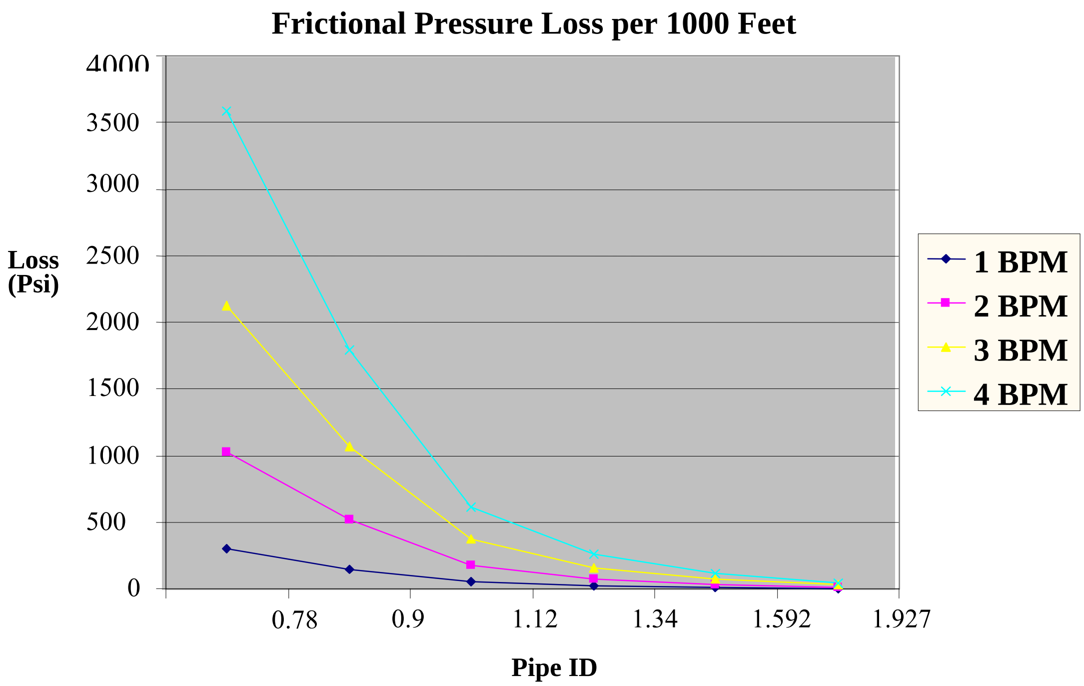
With regard to the intended scope of this task, the LANL document was listed primarily due to the fact that it documents current needs for further technology developments in sub-components such as micro-drill motors, bits of various nature, sensing, control and telemetry improvements as well as a need for better hydraulic modeling capabilities. According to the LANL study, " In order for micro-drilling to reach a depth of 5,000 feet, the hydraulic system must be optimized. Accurate simulation provides the most efficient means to achieve a first cut at optimization." Again, the complexity of fluid dynamic with respect to micro-drilling, is an area that needs to be defined by modeling and simulation. "Published flows versus pressure-drop models start with Newtonian laminar and turbulent flow then introduce corrections for non-Newtonian fluids, annular flow, eccentricity, skew and drill cutting concentration and transport. Each correction introduces small errors to the calculated results so large that errors cannot be ruled out in predictions of annular flow where all of these corrections must be applied". Further, industry experts have discovered that annular pressure losses will always exceed current predictions when utilizing current methods of analysis and this has been proven through actual field experience. A method for developing more accurate models is needed in order to optimize rheological parameters and the annular gap to support drilling over a wide range of depths, penetration rates, cutting size distribution as well as optimizing the tubing size with respect to product transfer to the surface. Having mentioned the need for further development of modeling capabilities, this may define the reason regarding the lack of creditable and available information regarding fluid dynamic for both drilling and production. The LANL study further defines five critical areas for needed technology development as well as five less critical areas. However, due to the length and complexity of the findings, with respect to the intended scope of this document, they will not be included at this time.

2.9 Precision Tubing Technology: Coiled Tubing Technical Handbook

Author: Precision Tubing Technology

Summary

The technical handbook from Precision Tubing Technology provides a working platform for data regarding coil tubing. It provides mechanical properties, frictional coefficients, definitions and calculations among other factors that include frictional pressure drop curves. The pressure drop curves can serve as an indicator regarding fluid flow and potential production rates in term of Barrels Per Minute (BPM). However, it should be understood that these curves were generated based on relatively simplistic models and may not consider more complex issues or conditions that occur during product transport. The following graph depicts pressure drop in (psi) with respect to the measured inside diameter of the tubing in inches. The approximate production rates are listed in Barrels per Minute (BPH) per 1,000 Ft. of length.



3.0 Fluid Flow Expert Contact Information / Key Knowledgeable Persons

The following list includes companies and universities that were contacted and/or are considered subject matter experts in the field of fluid dynamics, well exploration, drilling, production and coil tubing manufacturing.

3.1 Los Alamos National Laboratory (LANL)	
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4.0 Conclusion

Although we have identified significant research conducted on fluid dynamics that defines a host of critical problems and various solutions associated with CTD, the research, the data and the comments from subject matter experts indicate the need to further develop research tools and methodologies regarding fluid flow and the rheology of critical fluid dynamic issues. Such critical issues include, but are not limited to, the various flow regimes and phenomenon that are encountered when various fluid combinations are present in the flow stream. A simplistic example of this would be a water dominated flow or an oil dominated flow. Within these two flow regimes, there are sub-categories that include, but are not limited to, a dispersion of oil and water; a very fine dispersion of oil and water; and an oil and water chum or churn flow. Furthermore, within these flow regimes there exist flow transition patterns that have been modeled, analyzed and characterized in various papers some of which are included in this document. Issues that are more complex may include, but are not limited to, factors such as upward two-phase flow, flow pattern transitions and hydrodynamics, slug dynamics, slippage and velocity contour for power law fluids in an eccentric and concentric annulus.

Having mentioned a few of the simplistic as well as the more complex issues regarding fluid dynamics as they relate to CTD and subsequent production, it is important to mention and recognize that these issues have several criterion in common. Among the areas of commonality include:

- The issues mentioned and listed in this document in no way represent an all inclusive package for fluid dynamic or fluid motion scenarios particularly from a production standpoint primarily due to the lack of data available within the targeted tubing diameters.

- All of the fluid dynamic issues mentioned are critical to both drilling and production. Additionally, there are more factors that could be identified specifically for production if additional research is conducted and assuming that proper modeling capabilities have been achieved.

- The data included in this document should be considered application specific. This is defined by the diameter of tubing that was used for the model, the type of fluid, the inclination angle, pump rate, viscosity etc.

- In actual on-site application, or proper modeling, all data then becomes site-specific based upon the geological strata of the intended well.

- Additional research is required to develop modeling capabilities to accurately determine the fluid dynamics in smaller tubing sizes ranging from 3.00" to 1.00". This development or evolution process may result in generating an adequate code that will address all the fundamental requirements when dealing with fluid dynamics and adequately characterizing the fluid rheology with the well bore.

To summarize the data compiled in this document with respect to the literature search, various interviews with subject matter experts, and the recommendations identified in the Los Alamos National Laboratory, "Roadmap for a 5000-FT Micro-Bore-Hole", it is apparent that additional research is required to model fluid dynamics particularly in tubing ranging in size from 3.00" to 1.00". Maurer Technology, one of the collaborators in developing the road map with LANL, has developed a computer simulation code called "Oil Patch". Additional codes such as "Mudlite" and "Geotemp" are currently used in establishing well models. However, after discussions with industry experts and although these code are accepted in the industry, there are fundamental areas or an input of a combination of variables required for accurate modeling that are not readily available in these codes. For example a two parameter model requires less variable input than the more complex three parameter model and it is argued, the three parameter model is more accurate when modeling or defining the dynamics of fluid motion in a wellbore. Furthermore, listed in the paper, "Productivity and Injectivity of Horizontal Wells" the following codes were used for the completion of this paper which include:

- Mechanistic Model for Multiphase Pipe Flow
- Productivity of Horizontal Wells
- Optimum Horizontal Well Length Calculation
- Wellbore/Reservoir Coupling
- Well Pressure Profile Calculation
- Correlation for Cresting behavior in Horizontal Wells\Analytical Solutions for Critical Cresting Rate in Horizontal Wells

As mentioned, "It required the use or development of all of the above named codes to produce the analytical data listed in this paper". The paper also states " that not all of the programs written for this research project are suitable for distribution to practicing petroleum engineers. It recommends that industry engineers refer to a self-extracting file called SSD098.exe and once expanded, it provides several other directories and a file called DOE.html, which can be opened and viewed by any browser to initiate the analysis process.

It is also understood that certain industry sources have developed codes for modeling that are more advanced, sophisticated and may handle multiple input parameters or possibly be capable of analyzing three parameter models. An example of this would be BJ Service Company of Calgary, Canada where the home office for the companies CTD efforts is located. BJ is one of the more progressive leaders in both CTD and technology development. BJ Service worked in conjunction with the Coil Tubing Research and Engineering Centre, in Calgary to development a host of new process technologies, make performance improvements to existing technologies and initiate new tooling concepts. One of BJ's (or their predecessors) continuous development processes is with regard to a "home grown" software program called CIRCA. BJ developed the code over twenty-years ago primarily as a hydraulic model of coil tubing circulation of fluid in a well. After twenty-years of use and development, they have recently released CIRCA 14.2.4. Another valuable, "home grown" software tool developed by BJ is the CYCLE program that collects and analyzes information from every trip in and out of the well bore. However, due to the in house expense for developing these codes and the industry advantage they may provide, these codes are understandable treated as proprietary and are not commercially available.

Within the government funded research projects regarding micro-drilling, the majority of the conclusions state the need for industry to become involved and participate in a greater role than has been experienced to date. Although this is a fair statement to render, it is believed that various issues could be hindering industry involvement particularly the small producers. Among the issues that could be identified, are;

- The lack of in-house R&D resources to dedicate to the project, particularly with small producers.
- The lack of interest in a relatively un-proven technology (to the depths of 5,000 ft.), or the lack of accurate information that would prove the feasibility of micro-holes as a viable production alternative and or the similarity to the slimhole drilling or all of the above.
- Most drilling companies have a host of drilling equipment with maximum expected life cycle, depreciation schedule and salvage value. It may not be feasible or timely for them to invest in new technology that requires proven historical or theoretical data.
- The larger companies have internally funded R&D projects for the specific purpose of positioning the company in a more competitive position and will most likely maintain the developed technology as proprietary information.

In conclusion, it is recommended that a comprehensive study be conducted to define, model, analyze and characterize fluid dynamics within the targeted range defined by a micro-bore-hole. This study most likely will include the development of a computer code that provides the fundamental requirements to accurately model and characterize the fluid dynamic within the wellbore system. If a capable code is available or a code is developed to characterize the fluid dynamics, a study should be conducted in a manner that defines fluid requirements for both drilling and production and isolate any commonality found through analytical data as it is applied to tubing or borehole size. Of course, the code must be validated by creating analytical models that are tested in actual experiments in order to prove the accuracy of the code. The code should also be capable of modeling with under balanced conditions in addition to the application of various fluids and foams.

Furthermore, the code should be adaptable to industry, particularly the small producers, in a manner that utilizes a "user friendly" environment at an affordable cost.

The research could be conducted through a collaborative effort of subject matter experts, most of which are identified in this document. It is, however, extremely critical to provide specific task requirements in order to achieve the proper results for the range of tubing sizes as defined by micro-bore-holes.

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