TRANSIENT HYDRAULICS AND MULTIPHASE KICK TOLERANCE STUDY TO IMPROVE DESIGN OF NARROW MARGIN WELL

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To my beloved mother and father

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ABSTRACT

Hydraulic and well control studies are the essential parts of well construction planning, especially for drilling of complex and challenging wells with narrow drilling margins. However, the complete applications of dynamic hydraulic analysis and multiphase kick tolerance studies in well design are scanty, which result in ineffective mud pressure management and extra cost spent on unnecessary casing strings, due to excessive emphasis on previous practices (steady-state model) with liberal sprinkling of safety factors. This research project was set out clearly to improve the well design for narrow margin field, in terms of hydraulics and well control. A deductive quantitative method constitutes major part of the research methodology, in which simulation of real case studies and interpretation were conducted. The dynamic hydraulics simulated equivalent circulating density (ECD) was compared with steady-state results in terms of accuracy and extensiveness in providing a good well design. In addition, the single bubble kick tolerance results which are commonly used by the industry in spreadsheet format were compared with the multiphase model results. Sensitivity studies were performed to understand the effect of each of the operational or well design parameters towards primary and secondary well control. As compared to steady-state hydraulics, transient model covers important parameters like pressure and temperature dependent fluid properties, thermophysical properties, detailed geometry description and operational effects, thus it is more representative to the operational ECD. Meanwhile, multiphase kick model is proven to be more effective for the evaluation of kick tolerance as it is able to provide the information of pressure development during a well control operation, from initial influx and shut-in until influx is circulated out of the well at the surface. This includes all phase transitions including dissolving of a gas kick in oil based mud and breakout of free gas when the gas contaminated mud reaches the bubble point at shallower depth in the well. The flow model is much more accurate and reliable than the over-conservative traditional single bubble theory.

ABSTRAK

Kajian kawalan telaga dan hidraulik ialah komponen yang penting dalam perancangan untuk membina telaga terutama bagi penggerudian yang rumit dan mencabar dengan margin tekanan yang sempit. Namun begitu, tahap kesedaran yang rendah tentang kepentingan penganalisisan hidraulik dinamik dan toleransi tendangan multifasa dalam kerja mereka bentuk telaga telah menjejaskan keberkesanan pengurusan tekanan lumpur. Akibatnya, kos tambahan diperlukan untuk pemasangan rentetan selongsong berikutan penekanan terhadap model keadaan mantap yang sentiasa memberikan margin keselamatan secara berlebihan. Kajian ini bertujuan untuk memperbaik reka bentuk telaga yang menghadapi margin tekanan yang sempit, dari segi kawalan telaga dan hidraulik. Kajian secara kuantitatif and deduktif ini melibatkan penyelakuan kes telaga sebenar dan pentafsirannya. Ketumpatan peredaran setara (ECD) yang diperoleh daripada penyelakuan hidraulik dinamik telah dibandingkan ketepatan dan rangkumannya dengan keputusan daripada model keadaan mantap bagi menghasilkan reka bentuk telaga yang baik. Di samping itu, keputusan toleransi tendangan gelembung tunggal yang menjadi amalan industri turut dibandingkan dengan hasil daripada model multifasa. Kajian kepekaan dilaksanakan untuk memahami kesan setiap parameter operasi dan reka bentuk telaga terhadap kawalan telaga utama dan sekunder. Model hidraulik dinamik yang mencakupi parameter penting, misalnya sifat bendalir yang peka terhadap suhu dan tekanan, sifat termo-fizikal, huraian geometrik telaga, dan kesan operasi, didapati mampu memberikan keputusan operasi ECD yang lebih praktikal berbanding model keadaan mantap. Selain itu, model tendangan multifasa adalah lebih jitu dalam penilaian toleransi tendangan kerana model terbabit mampu memberi maklumat tentang perubahan tekanan ketika operasi kawalan tekanan, bermula daripada berlakunya tendangan gas dan kurungan, hingga ke bendalir tendangan dikeluarkan di permukaan. Maklumat turut mencakupi perubahan semua fasa termasuk keterlarutan gas tendangan di dalam lumpur dasar minyak dan pelepasan gas bebas bila lumpur yang dicemari gas mencapai takat gelembungnya pada kedalaman yang dangkal. Model aliran ini ternyata lebih tepat dan boleh dipercayai berbanding teori gelembung tunggal yang konservatif.

TABLE OF CONTENTS

3 RESEARCH METHODOLOGY

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AMSL - Average Main Sea Level
BHA - Bottom Hole Assembly
BHP - Bottom Hole Pressure
BHT - Bottom Hole Temperature
BOP - Blowout Preventer
DP - Drill Pipe
ECD - Equivalent Circulating Density
ESD - Equivalent Static Density
FBHP - Flowing Bottom Hole Pressure
gpm - Gallons per minute
GUI - Graphic User Interface
ID - Inner Diameter
IWCF - International Well Control Forum
KT - Kick Tolerance
MD - Measured Depth
OBM - Oil Based Mud
OD - Outer Diameter
PI - Productivity Index
ppg - Pounds per Gallon
RKB - Rotary Kelly Bushing
SDM - Synthetic Based Mud
TD - Total Depth
TFA - Total Flow Area
TOC - Top of Cement
TVD - Total Vertical Depth
WBM - Water Based Mud

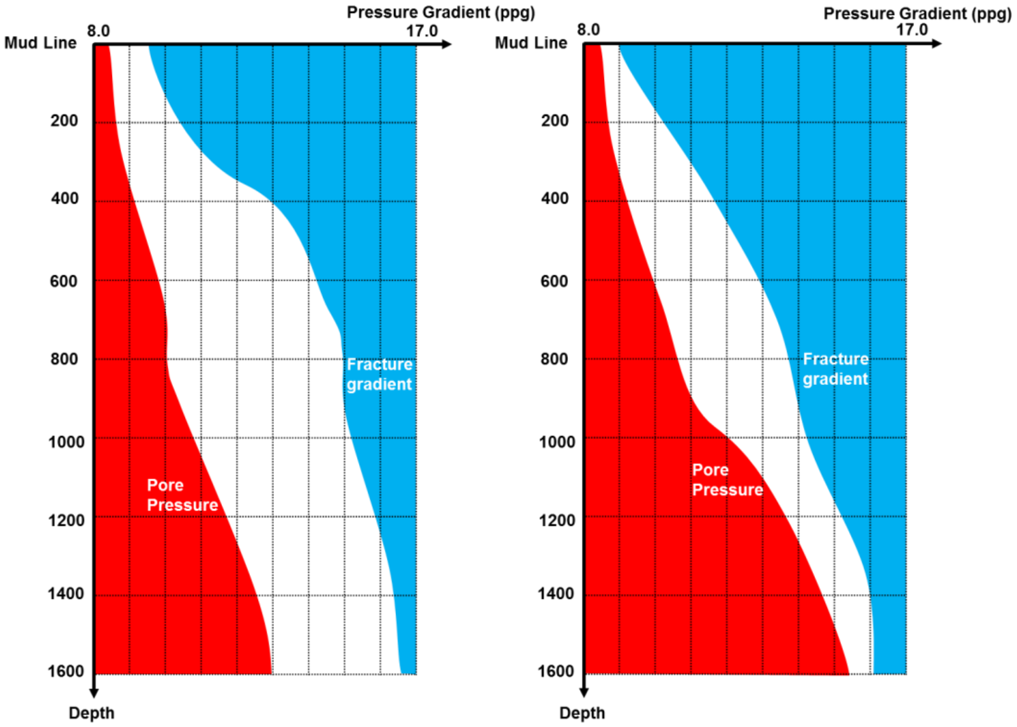
LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Well construction activities are executed within a pressure window bounded on the lower side by reservoir pressure (is also known as pore pressure) and on the upper side by the fracture pressure of the formation in an openhole (Figure 1.1). As the drilling continuously expands into harsher and high complexity terrains, the pressure window can be very narrow as less than 1 ppg, requiring the operations to be performed by walking the tight rope between these limits.



(a) (b)

Figure 1.1 Normal drilling margin (a) and narrow drilling margin <1ppg (b)

Thus, conventional drilling methods typically become strained when attempting to drill wells with narrow operational windows (Li *et al*., 2012). For instance, non-productive time to drilling operational problems, such as kicks, loss circulation, and stuck pipe events are commonly mount and result in hefty cost (Noniface and Marcus, 2014).

Several subsurface settings can contribute to narrow margin, such as increasing of water depths and widely varying formation pressures (Figure 1.2). Particularly in deepwater environment, the high water depth alters the subsurface pressure profiles by decreasing the overburden stress on the formation, which eventually translates to a reduced fracture gradient in the vicinity of the wellbore. Meanwhile the pore pressure gradient is typically determined by hydrostatic head of overlying fluid, therefore it is not affected by the water depth (Rocha *et al*. 2004).

Apart from that, the presence of abnormal pore pressure pockets (where the pore pressure is greater than hydrostatic pressure) further reduces drilling margin. These pockets are originated from tectonic movements, salt dome effects, under-compaction, as well as chemical and thermal actions (Freire *et al.*, 2010). The ensuing challenges share a commonality relating to safe navigation between the drilling margins.

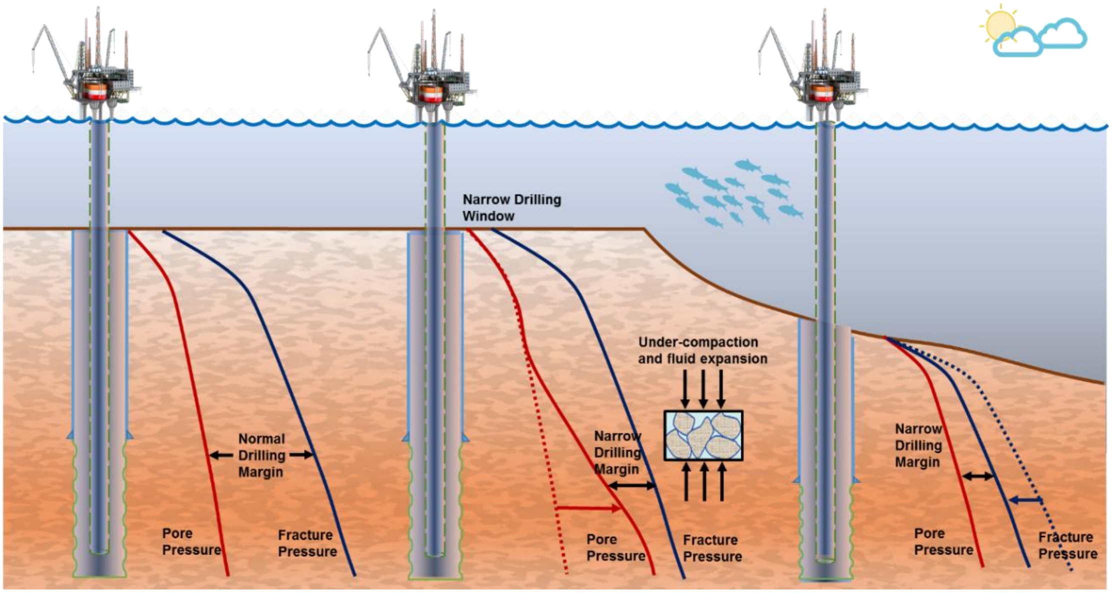
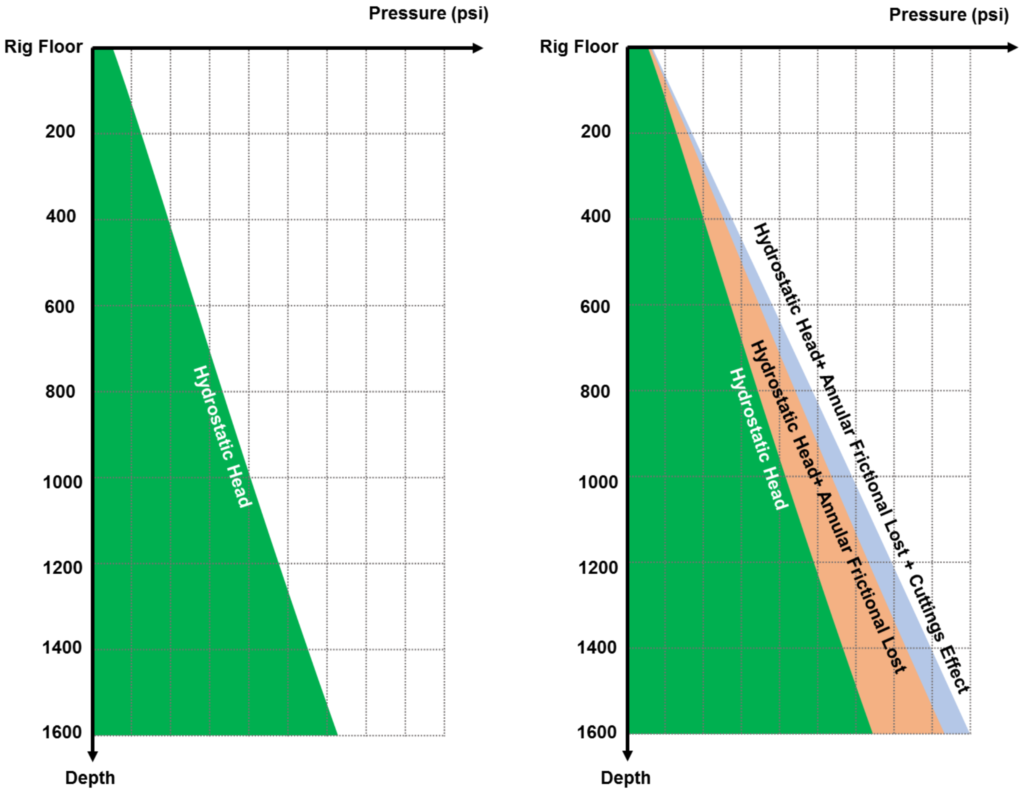


Figure 1.2 Increasing water depth and under-compaction narrow the drilling margin

The hydrostatic pressure created by the drilling fluid column is commonly expressed as equivalent static weight (ESD), by relating the pressure at a specified depth to its corresponding fluid density. During circulation conditions, the mud creates an equivalent circulating density (ECD) which is higher than ESD. Referring to IADC Lexicon, ECD, in the unit of ppg, is defined as the summation of fluid's hydrostatic pressure, cuttings, and annular friction pressure loss divided by vertical depth and by 0.052 (API RP59, 2012). ESD and ECD (Figure 1.3) must be kept between pore pressure and fracture pressure gradients throughout the drilling process. Once the wellbore pressure falls below the pore pressure, an influx of wellbore fluids can lead to a kick or even an underground blowout. Similarly, excessive hydrostatic pressures must also be avoided, as it can initiate and propagate fractures, which will cause loss of circulating fluid into the formation (Stave, 2014).



(a) (b)

Figure 1.3 Equivalent static density (a) and equivalent circulating density (b)

Figure 1.4 illustrates the drilling window of a hypothetical well, the pressure is represented by the step profile created when a successively heavier mud is used (vertical line) and the wellbore is drilled to a maximum depth in which mud pressure approaches pore pressure (horizontal line) which a casing is set.

In addition to ECD and ESD computation, the well design has to take consideration of kick effect in which every section must be able to withstand the well killing pressure without exceeding the fracture pressure. The maximum volume of gas kick in barrels, known as kick tolerance is usually set by operator as a well design standard which measure the integrity of the openhole to successfully shut in during kick event and circulate the kick out of the hole without breaking the weakest anticipated formation straight in wellbore (usually at previous casing shoe) (Redmann, 1991).

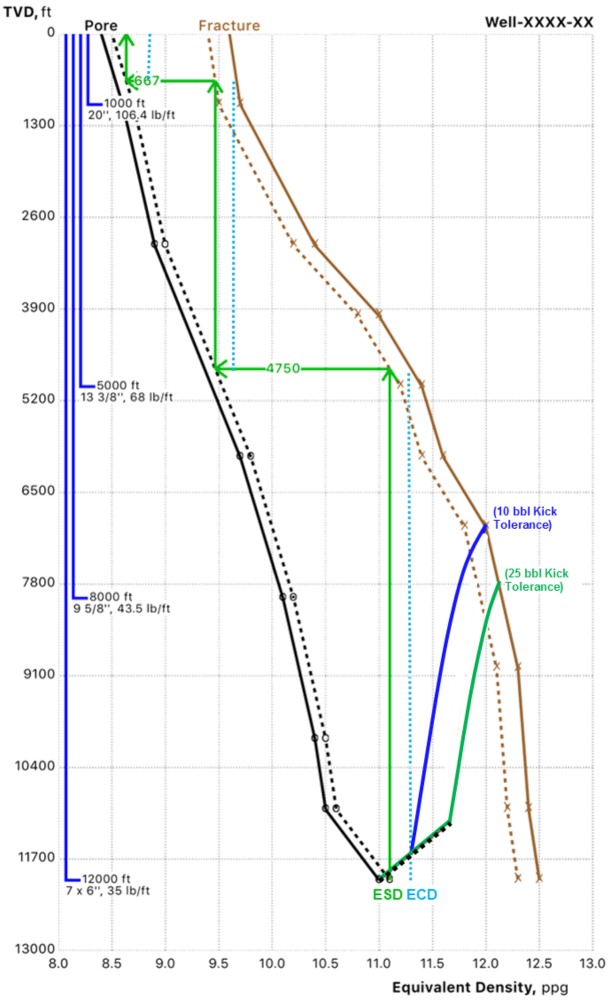


Figure 1.4 Well design plot

For instance, the section of 8.5 in hole requires 25 barrels kick tolerance as per well design standard of the operator. Based on the bottom-up casing seat design method, by using 11.1 ppg mud, the previous casing shoe can be set at 5000 ft., however, due to kick tolerance compliance, additional casing is set at 8000 ft. before drilling to total depth (TD) at 12000 ft..

Generally, the challenges of the narrow margin drilling can be divided into two main categories:

1. Drilling mud pressure variation

The series of standard drilling operations comprise of start and stop pumping intervals as drill pipe connections are made during tripping and drilling operations. When circulation stops, static conditions apply in the wellbore, and bottom-hole pressure (BHP) is determined solely by the mud column hydrostatic pressure. Restarting the pump will bring the well back into a dynamic state, thereby increasing downhole pressure and re-establishing ECD. Such variances in bottomhole condition can present added challenges, especially when seeking to maintain wellbore pressure within a window.

Moreover, mud pressure changes based on well depth, thus there is a high delay time of changing wellbore pressure when required as mud must first be mixed on the surface and circulated downhole. In addition of relying on the MWD data, pressure simulator is used to model and predict the downhole pressures, in order to give a quick look ahead to gauge the hydraulics condition and precise control of ECD.

2. Casing string usage

In order to reach the target depth in narrow margin condition, the excessive use of casing string is required. This is necessary to prevent mud losses as mud density is incrementally elevated to contain wellbore pressure. Furthermore, the compliance to kick tolerance worsens the case as additional casings are necessary to ensure well integrity during well control events (Leblanc and Lewis, 1968). Further to heightened expenses and drilling time, extra casing string can affect the production performance as the flow area becomes smaller.

1.2 Problem Statement

As mentioned in the earlier section, the narrowing of the operating margin available within the drilling window increases the technical challenges associated with drilling operations. Strategic planning always yields huge improvement potential and provides the highest impact on well performance without compromising the safety aspect. First and foremost, in terms of drilling hydraulics, the need of accurate computation of ESD and ECD is important in this case as it would optimize the well design and determine the safe drilling and casing depths.

The steady-state hydraulics model is widely used by the well engineers during planning phase which the magnitude of ECD is constant with time throughout the entire domain analyzed at certain bit depth. Figure 1.5 shows the results of steady-state hydraulics study which the ECD and ESD values are usually computed when the drilling bit reaches TD. These results do not change in time, in which symbolize that the bit reaches TD with certain rate of penetration (ROP) and circulation rate, drilling operation is performed continuously until the ECD reaches static condition. This condition is impossible as during drilling operation, the ECD has been observed to be sensitive to cuttings and temperature changes, and also it does not explain how the ECD varies starting with the operations of drilling out cement, making-up connection, continuing drilling until TD, and hole cleaning. Multiple runs of computation have to be performed in order to understand the whole well construction hydraulics effect.

Therefore, steady state hydraulics does not represent the operation condition and most of the time the steady state model does not take into account parameter such as fluid thermal effect and temperature profiles, cuttings (slip) effect, mud gel strength effect, pressure-volume-temperature (PVT) relationship of the mud, etc. (Rommetveit and Bjorkevoll, 1997). A good well design with narrow margin requires an in-depth understanding of the transient hydraulics during all phases of the operation. The drilling process is usually highly dynamic and complicated to model, thus, transient modeling of drilling hydraulics has traditionally been neglected, although the model is able to replicate a real drilling operation and provide a more accuracy prediction than steady-state models.

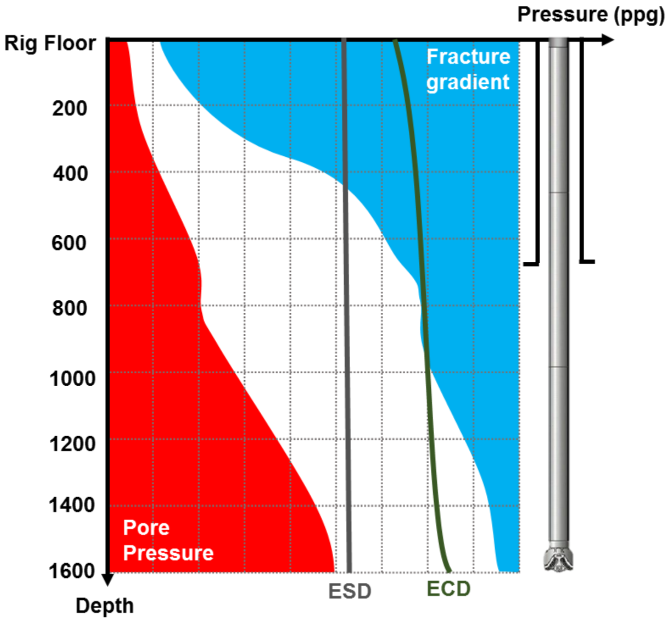


Figure 1.5 Steady-state hydraulics results

Admittedly, kick tolerance is a key element when establishing a well design. Apart from the mud weight design, the number of hole sections also relies on the kick tolerance results computed using simple spreadsheet, which certain volume of kick must be bearable by each sections (Wessel and Tarr, 1991). NORSOK (2004) states that the recommended kick tolerance for each section size and the operators have their own standard values which governs their well integrity, as a measure to prevent underground blowout. However, neither the American Petroleum Institute (API) nor International Association of Drilling Contractors (IADC) provides the method for computing kick tolerance.

Generally, the kick tolerance is very well defined in open literature, the kick models consider single gas bubbles (Figure 1.6) with simplifications regardless the effect of frictional pressure loss during killing operation, equipment handling delay, gas migration rate and gas solubility in oil based fluid (Mosti *et al*., 2017). The assumptions are made too conservatively to ensure strict compliance for safety and simplicity (Denney, 2012). The single gas bubble model does not characterize the actual downhole behavior during a kick scenario, and the condition of single bubble is impossible to happen (Santos *et al*. 2011). Conservative designs may increase costs or prohibit drilling due to safety concerns, it does not mean the narrow margin well is impossible to drill. A comprehensive optimization kick tolerance study is achievable by multiphase kick modeling without compromising the safety and drilling standards.

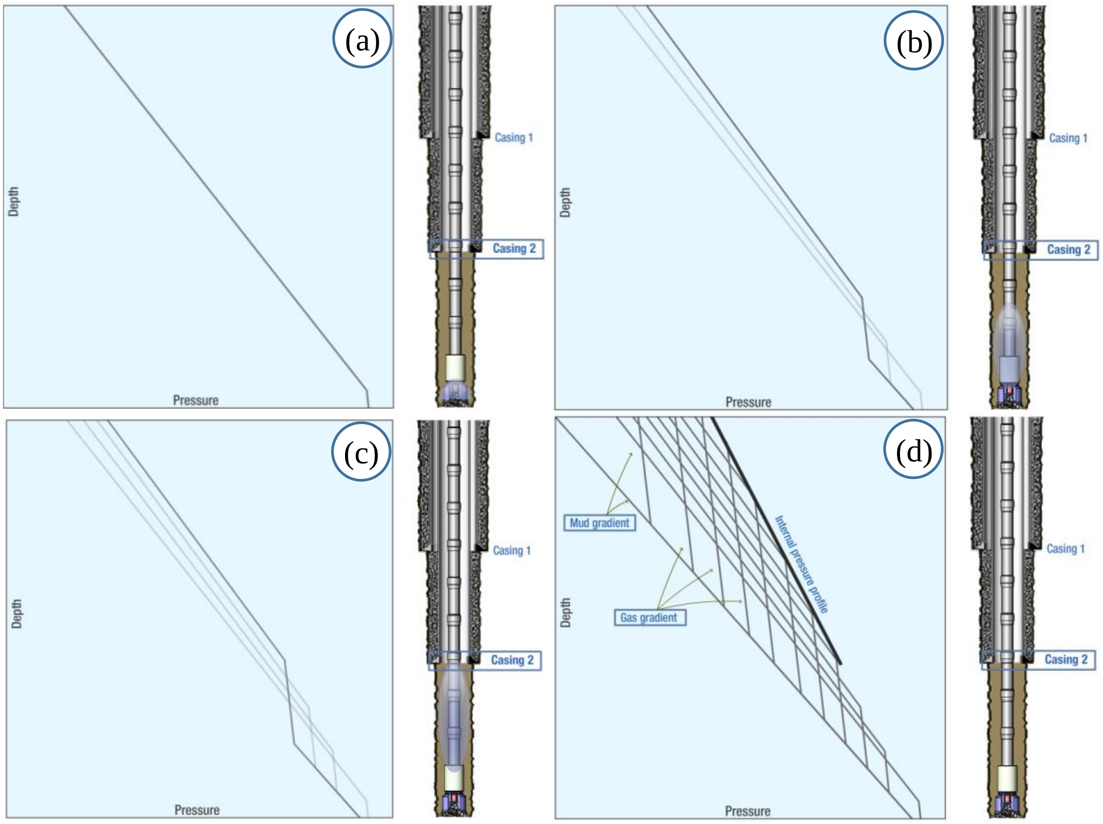


Figure 1.6 The single bubble gas kick expands when circulated out of well and create pressure upsurge: (a) A well control event starts with a gas influx, with pressure gradient of 0.1 psi/ft. at the bottom of the well, (b) Gas bubble expands while traveling up, (c) The casing shoe depth experiences the highest pressure when the top of gas reaches the casing shoe depth, (d) The overall annular pressure profile during well killing is greater than mud hydrostatic pressure, larger influx yields higher pressure.

1.3 Hypothesis

The detailed modeling of hydraulics in transient mode and multiphase kick tolerance can assist in understanding better the degree of drillability of the narrow margin hole which subsequently can improve the well planning. Hypothetically, an accurate dynamic hydraulics model combines transient effects with a detailed specification of fluid properties and geometry allows engineers to view the ECD in time and develop, in order to promote effective pressure control and efficiently reach the well's objectives. ECD rises with the increase of mud pumping rate, mud weight used, fluid viscosity, circulation time, and rate of penetration. Contrariwise, it declines with the increase of temperature, rotational speed of the drill string, annular flow area, and drilling depth.

During gas migration, the influx interacts with the mud and dissolves in the oil phase of the mud until it reaches the bubble point condition at shallow depth. At bubble point, it pops out from the oil and starts to expand. In the water-based mud, the influx does not dissolve, instead it expands once it enters the well, with certain liquid hold up (Umar et al., 2014). The single-bubble models cannot represent these dynamic processes and often provide unrealistic results with higher casing shoe pressure.

1.4 Objectives

The objectives of the research cover the hydraulics and well control study specifically for narrow margin wells:

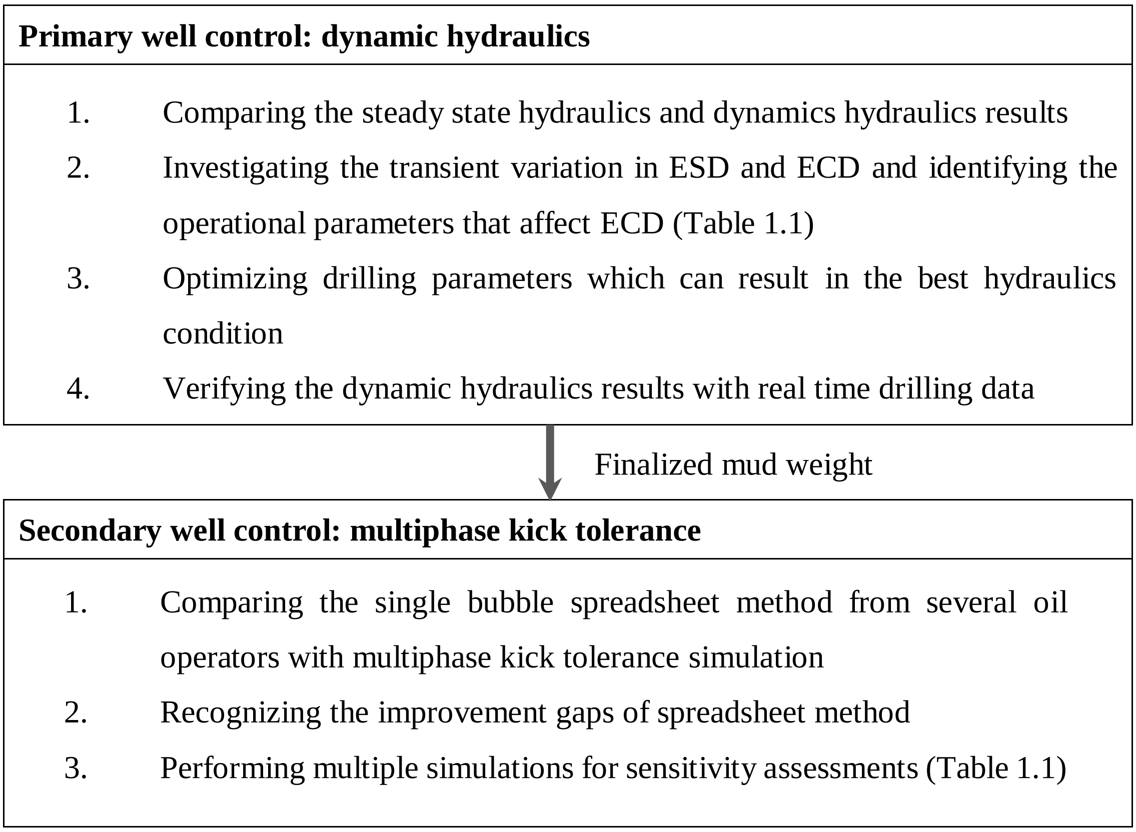
1. To improve current steady-state drilling hydraulics study to transient model, which can be a precise representation of operational equivalent circulating density and offer strong potential to significantly impact the effectiveness of well design and operations. It delivers quantum value to oil operators in terms knowledge gained to achieve the operational excellence and reduce non-productive time. It informs better operational planning and provide more

effective means of dealing with the narrow margin challenges in exploration projects.

2. To model accurate multiphase kick tolerance which can improve the effectiveness of the single bubble kick tolerance concept. The research outcome can eliminate the need of unnecessary budget as the well is deemed undrillable with too many casings or on the other hand an unreliable value that could put in jeopardy the achievement of the drilling and safety objectives.

1.5 Research Scope

The research scope (Figure 1.7) focuses on the well design using the simulation of realistic operation, covering the hydraulics changes in operational parameters over time (circulating, static, drilling, and tripping) and multiphase kick tolerance analysis.



Primary well control: dynamic hydraulics

1. Comparing the steady state hydraulics and dynamics hydraulics results
2. Investigating the transient variation in ESD and ECD and identifying the operational parameters that affect ECD (Table 1.1)
3. Optimizing drilling parameters which can result in the best hydraulics condition
4. Verifying the dynamic hydraulics results with real time drilling data

Secondary well control: multiphase kick tolerance

1. Comparing the single bubble spreadsheet method from several oil operators with multiphase kick tolerance simulation
2. Recognizing the improvement gaps of spreadsheet method
3. Performing multiple simulations for sensitivity assessments (Table 1.1)

Figure 1.7 Research scope

Table 1.1 Data input and parameters for research

Simulation cases	1. Shallow water slanted well with pore pressure ramp (overpressured reservoir) 2. Deep water vertical well with narrow margin drilling window
Sections	12.25 in. and 8.5 in.
Parameters for ECD study	1. Mud temperature effect 2. Mud viscosity 3. Rate of Penetration / Cutting loadings 4. Drill string rotational speed and torque 5. Annular flow area 6. Mud weight
Kick tolerance sensitivity study parameters	1. Water based or oil based mud 2. Kick intensity 3. Swabbed kick and drill kick scenario
Exclusions and assumptions	1. The centrifuge effect of drill string rotational on cuttings is negligible. 2. Normal drilling scenarios are simulated, managed pressure drilling and dual gradient drilling conditions are not studied. 3. Kick tolerance study with influx of pure methane is presumed to happen at TD of each hole section, at constant rate of 3 bbl/min. 4. Surge, swab effect and cementing pressure are not studied. 5. Driller's method is used for well control modeling. 6. Glasso oil PVT correlation model and Dodson-Standing water PVT correlation model are used to model the mud density. 7. Mud rheology model of Roberton-Stiff is used to represent the correlation of shear rate and shear stress of the mud.

1.6 Significance of Study

The narrow margin well condition creates the need to look beyond the traditional way of well planning (steady state modeling) to increase operational margin. Modeling the wells dynamically is essential and strategically important in order to replicate the real drilling operations and provide accuracy which is not possible with steady-state models. The transient analysis increases the drillers' confidence in accessing to this challenging field safely that would otherwise have been near impossible to drill without understanding of the pressure control. This rigorous approach in wellbore pressure management has led the engineers to decision making, cost saving, and reaching maximum drillable depth safely.

Dynamic modeling in hydraulics and well control of a narrow margin deep water hole delivers accurate predictions of wellbore pressure and temperature, linking of safe drilling practices with drilling efficiency. The casing seat and maximum drillable depths are optimized based on multiphase kick tolerance. The comprehensive study of drilling hydraulics and kick tolerance thus offers strong potential to positively impact well planning and operational practices for the operators.

1.7 Chapter Summary

The scope of studies covers primary and secondary well control of narrow margin well which can be set as the best practice for operators to increase the confidence in exploring or drilling the tight-margin well safely. The subject background, objectives, research scope and significance of study were outlined to realize the proposed research work and to understand the need of author to explore more in this field of study.

REFERENCES

Abdul-Majeed, G. H. and Salman, N. H. (1988). An Empirical Correlation for Oil FVF Prediction. *Journal of Canadian Petroleum Technology*. 27(06), 118-122. Petroleum Society of Canada.

Al Hajeri, M., Al Safar, W., Gupta, P. K., Raturi, S. K., Al Zankawi, O., Bojarah, K. H., Abdessalem, A. (2017). Wellbore Stability Management to Avoid Serious Drilling Hazards in High Deviated Well-Application of Real Time Geomechanics. *SPE Abu Dhabi International Petroleum Exhibition & Conference*. 13-16 November. Abu Dhabi, UAE.

Al-Marhoun, M.A. (1988), PVT Correlations for Middle East Crude Oils. *Journal of Petroleum Technology*. 40(5), 650-666. Society of Petroleum Engineers.

Al-Marhoun, M.A. (1992). New Correlations for Formation Volume Factors of Oil and Gas Mixtures. *Journal of Canadian Petroleum Technology*. 31(03), 22-26. Petroleum Society of Canada.

American Petroleum Institute (2012). *API RP 59 2012: Recommended Practice for Well Control Operations, 2nd edition*. Washington, D.C.: American Petroleum Institute.

Beirute, R. M. and Flumerfelt, R. W. (1977). An Evaluation of the Robertson-Stiff Model Describing Rheological Properties of Drilling Fluids and Cement Slurries. *Society of Petroleum Engineers Journal*. 17(02), 97-100. Society of Petroleum Engineers.

Bell, J.S. and Gough, D.I. (1979). Northeast-Southwest Compressive Stress in Alberta: Evidence from Oil Wells. *Earth and Planetary Science Letters*. 45(2), 475-482. Elsevier.

Bernard, H. R., and Bernard, H. R. (2012). *Social research methods: Qualitative and quantitative approaches*. New York: Sage Publications.

Bingham, E.C. (1916). An investigation of the laws of plastic flow. *U.S. Bureau of Standards Bulletin*. 13, 309-353. National Bureau of Standards.

Boniface, O. A. and Marcus, N. M. (2015). A Model to Determine the Effect of Pore Pressure and Fracture Gradient on Stuck Pipe Management. *Nigeria Annual International Conference and Exhibition.* 4-6 August 2015, Lagos, Nigeria.

Business Monitor International (2017). *Exploration & Production Software Market - Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2016 - 2024*. Retrieved May 1, 2017 from http://www.reportlinker.com/p04772283

Changjun L., Wenlong J. and Xia W. (2011). Modeling and Simulation for Steady State and Transient Pipe Flow of Condensate Gas. In Moreno-Piraján J. C. (ed): *Thermodynamics: Kinetics of Dynamic Systems*. pp 65–84. Rijeka, Croatia: Intech Books.

Creswell, J. W. (2002). *Educational research: Planning, conducting, and evaluating quantitative*. New Jersey: Prentice Hall.

Creswell, J. W. (2013). *Research design: Qualitative, quantitative, and mixed methods approaches*. New York: Sage Publications.

Denney, D. (2012). Kick-Tolerance Misconceptions and Consequences for Well Design. *Journal of Petroleum Technology*. 64(01), 85-88. Society of Petroleum Engineers.

Dodson, C. R., & Standing, M. B. (1944). Pressure-Volume-Temperature and Solubility Relations for Natural-Gas-Water Mixtures. *Drilling and Production Practice*. 173-179. American Petroleum Institute.

Dokla, M., & Osman, M. (1992). Correlation of PVT Properties for UAE Crudes. *SPE Formation Evaluation*. 7(01), 41-81. Society of Petroleum Engineers.

Edwards, J. H. (1964). Engineering Design of Drilling Operations. *Drilling and Production Practice*. 1 January. New York, United States.

Francois C., G. M., Diane N., Graham R., Randy H., Dominic M. and Laurent P. (1998). Planning and Drilling Well in the Next Millennium. *Oilfield Review Winter 1998*. 10(04), 3-13. Schlumberger Oilfield Review.

Freire, H. L. V., Falcao, J. L., Silva, C. F. and Barghigiani, L. M. (2010). Abnormal Pore Pressure Mechanisms in Brazil. *44th U.S. Rock Mechanics Symposium and 5th U.S -Canada Rock Mechanics Symposium.* 27-30 June. Salt Lake City, Utah.

Gall, M. D., Borg, W. R., and Gall, J. P. (2003). *Educational research: An introduction*. (7th Edition). White Plains, New York: Longman.

Gao, Y., Sun, B., Xu, B., Wu, X., Chen, Y., Zhao, X. and Chen, L. (2016). A Wellbore–Formation-Coupled Heat-Transfer Model in Deepwater Drilling and It's Application in the Prediction of Hydrate-Reservoir Dissociation. Preprint, 1-11. *SPE Journal*. Society of Petroleum Engineers.

Glaso, O. (1980). Generalized Pressure-Volume-Temperature Correlations. *Journal of Petroleum Technology*. 32(05), 785-795. Society of Petroleum Engineers.

Gulati, PM. (2009). *Research Management: Fundamental and Applied Research*. India: Global India Publications.

Halliburton (2016). *WellPlan Software.* [Brochure]. Houston, Texas.

Hansen, K. S., Wang, G., Adeleye, O., McNeil, K. V., Couzens-Schultz, B. A., Azbel, K., and Tare, U. (2014). Integrated Predrill Pore-Pressure and Borehole-Stability Prediction for Prelude Development. *SPE Drilling & Completion*. 29(04), 418-430. Society of Petroleum Engineers.

Hilal, R., Mohammed, H., Lawati, A. B. A., Saud, K., Yan, T., Badar, Z., and Pranava, A. (2017). Successful Well Design Journey-Oman. *SPE Abu Dhabi International Petroleum Exhibition & Conference*. 13-16 November. Abu Dhabi, UAE.

Kabir, C. S. and Hasan, A. R. (1996). Determining Circulating Fluid Temperature in Drilling, Workover and Well-Control Operations. *SPE Drill & Completion* 9(1), 74-79. Society of Petroleum Engineers.

Karahasan, K., Oyovwevotu, J. S., and Vielma, W. E. S. (2017). Implementation of Dispersed Gas Model for Kick Tolerance Analysis of an HPHT Exploration Well in Norway. *SPE Abu Dhabi International Petroleum Exhibition & Conference.* 13-16 November . Abu Dhabi, UAE.

Kartoatmodjo, T. and Schmidt Z. (1994). Large Data Bank Improves Crude Physical Property Correlation. *Oil Gas Journal*. 4, 51–55. Society of Petroleum Engineers.

Kasim, R., Alexander, K. and Hudson, J. (2010). *A choice of research strategy for identifying community-based action skill requirements in the process of delivering housing market renewal.* Research Institute for the Built and Human Environment, University of Salford, UK.

Kemp, N. P. and Thomas, D. C. (1987). Density Modeling for Pure and Mixed-Salt Brines as a Function of Composition, Temperature, and Pressure. *SPE/IADC Drilling Conference*. 15-18 March. New Orleans, Louisiana.

Lasater, J. A. (1958). Bubble Point Pressure Correlation. *Journal of Petroleum Technology*. 10(05), 65-66. Society of Petroleum Engineers.

Leblanc, J. L. and Lewis, R. L. (1968). A Mathematical Model of a Gas Kick. *Journal of Petroleum Technology*. 20(08), 888-898. Society of Petroleum Engineers.

Lesage, M., Hall, P., Pearson, J. R. A. & Thiercelin, M. J. (1991). Pore-Pressure and Fracture-Gradient Predictions. *Journal of Petroleum Technology*. 43(06), 652-654. Society of Petroleum Engineers.

Li, C., Liu, E. B. and Yang, Y. Q. (2009). The Simulation of Steady Flow in Condensate Gas Pipeline. *International Conference on Pipelines and Trenchless Technology 2009 (ICPTT 2009)*. 18-21 October. Shanghai, China: 733-743.

Li, S., George, J. and Purdy, C. (2012). Pore-Pressure and Wellbore-Stability Prediction to Increase Drilling Efficiency. *Journal of Petroleum Technology*. 64(02), 98-101. Society of Petroleum Engineers.

Lillian E. G., David P. and Jesse R. (2012). Real-time data offers critical tool to redefine well control, safety. In Complete, timely interpretation of well data a key opportunity for industry to improve process safety, ensure well containment. *Drilling Contractor: Drilling It Safely, November/December 2012*. (pp. 96-109). Houston, Texas: International Association of Drilling Contractors.

Liz-Losada, R. J. and Alejano, L. R. (2000). New Safe Mud Weight Window Representations to Prevent Wellbore Instability. *IADC/SPE Asia Pacific Drilling Technology*. 11-13 September. Kuala Lumpur, Malaysia.

Ma, Z., Vajargah, A.K., Ambrus, A., Ashok, P., Chen, D. van Oort, E., May, R., Macpherson, J.D., Becker, G. and Curry, D.A. (2016). Multi-Phase Well Control Analysis during Managed Pressure Drilling Operations. *SPE Annual Technical Conference and Exhibition*. 26-28 September. Dubai, UAE.

Madatov A. G. and Sereda A.V. (2006). The pre-drill and real time while drilling overpressure prediction based on effective basin model concept. *Research Gate*. 3(09), 361-388. Higher Mathematics Chair of the Polytechnical Faculty, MSTU.

Mosti, I., Morrell, D., Anfinsen, B. T., Vielma, W. E. S. and Nergaard, K. (2017). Kick Tolerance and Frictional Pressure Losses, Added Safety or Added Risk.

SPE/IADC Drilling Conference and Exhibition. 14-16 March. The Hague, the Netherlands.

Nickens, H.V. (1987). A dynamic computer model of a kicking well. *SPE Drilling Engineering*. 2(02), 159-173. Society of Petroleum Engineers.

NORSOK (2004). *D-010, Well integrity in drilling and well operations, Rev. 3*. Norway: Norsok.

Paradigm (2014). *Sysdrill, well planning and drilling enigneering.* [Brochure]. Brisbane, Australia.

Petrosky, G. E. and Farshad, F. (1998). Pressure-Volume-Temperature Correlations for Gulf of Mexico Crude Oils. *SPE Reservoir Evaluation & Engineering*. 1(05), 416-420. Society of Petroleum Engineers.

Punch, K. F. (2013). *Introduction to social research: Quantitative and qualitative approaches*. New York: Sage Publications.

R.L. Rowley (n. d.). *Transient_Balances: ChEn 273 Learning Resource Center*. Retrieved on April 7, 2017, http://www.et.byu.edu/~rowley/ChEn273/

Redmann, K. P. (1991). Understanding Kick Tolerance and Its Significance in Drilling Planning and Execution. *SPE Drilling Engineering.* 6(04), 245-249. Society of Petroleum Engineers.

Robson, C. (2002). *Real world research* (Vol. 2). Oxford: Blackwell Publishers.

Rocha, L. A. S., Falcão, J. L., Gonçalves, C. J. C., Toledo, C., Lobato, K., Leal, S. and Lobato, H. (2004). Fracture Pressure Gradient in Deepwater. *IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*. 13-15 September. Kuala Lumpur, Malaysia.

Rommetveit, R. and Bjorkevoll, K. S. (1997). Temperature and Pressure Effects on Drilling Fluid Rheology and ECD in Very Deep Wells. *SPE/IADC Middle East Drilling Technology Conference.* 23-25 November. Bahrain.

Samuel, G. R. (2010). *Formulas and calculations for drilling operations*. Salem, Massachusetts: Scrivener.

Santos, H. M., Catak, E. and Valluri, S. (2011). Kick Tolerance Misconceptions and Consequences to Well Design. *SPE/IADC Drilling Conference and Exhibition*. 1-3 March. Amsterdam, the Netherlands.

Santos, O., Adasani, I., Azar, J. J. and Escorihuela, F. (1995). Determination of Casing Setting Depth Using Kick Tolerance Concept. *Petroleum Computer Conference.* 11-14 June. Houston, Texas.

Schlumberger (2016). *Drillbench Dynamic Hydraulics, evaluate and understand the hydraulic barrier*. [Brochure]. Houston, Texas.

Schlumberger (2016). *Drillbench Dynamic Well Control, advanced well control engineering for planning and operations.* [Brochure]. Houston, Texas.

Simoes, S. Q., Miska, S. Z., Takach, N. E. and Yu, M. (2007). The Effect of Tool Joints on ECD While Drilling. *Production and Operations Symposium*. 31 March-3 April. Oklahoma City, Oklahoma, U.S.A.

Snieder, R. and Larner, K. (2009). *The Art of Being a Scientist: A Guide for Graduate Students and their Mentors*. Cambridge: Cambridge University Press.

Sorelle, R.R., Jardiolin, R.A., Buckley, P., and Barrios, J.R. (1982). Mathematical Field Model Predicts Downhole Density Changes in Static Drilling Fluids. *SPE Annual Technical Conference and Exhibition*. 26-29 September. New Orleans, Louisiana.

Standing, M. B. (1947). A Pressure-Volume-Temperature Correlation for Mixtures of California Oils and Gases. *Drilling and Production Practice*. 1 January. New York, United States.

Stave, R. (2014). Implementation of Dual Gradient Drilling. *Offshore Technology Conference*. 05-08 May. Houston, Texas.

Umar, L., Thiam, Y., Murad, M. S., Woo, W. K., Nas, S. W., Escalono, B. and Eka, A. (2014). Dynamic Multiphase Kick Tolerance Allows Safe Drilling Which Led to Huge Gas Discovery in a HPHT Exploration Well in Malaysia. *International Petroleum Technology Conference*.19-22 January. Doha, Qatar.

Vazquez, M., & Beggs, H. D. (1980). Correlations for Fluid Physical Property Prediction. *Journal of Petroleum Technology*. 32(06), 968-970. Society of Petroleum Engineers.

Weatherford (2017). *Steady-state Continuous Flow System*. Retrieved on May 1, 2017, http://www.weatherford.com/en/products-services/drilling-formation-evaluation/secure-drilling-services.

Wessel, M. and Tarr, B. A. (1991). Underground Flow Well Control: The Key to Drilling Low-Kick-Tolerance Wells Safely and Economically. *SPE Drilling Engineering.* 6(04), 250-256. Society of Petroleum Engineers.

Wilson, J. (2010). *Essentials of Business Research: A Guide to Doing Your Research Project*. New York: Sage Publications.

Yuan, H. and Zhou, D. (2009). Evaluation of Two Phase Flow Correlations and Mechanistic Models for Pipelines at Horizontal and Inclined Upward Flow. *SPE Production and Operations Symposium*. 4-8 April. Oklahoma City, Oklahoma.

Zoellner, P., Thonhauser, G., Lueftenegger, M., & Spoerker, H. F. (2011). Automated Real-time Drilling Hydraulics Monitoring. *SPE/IADC Drilling Conference and Exhibition*. 1-3 March. Amsterdam, the Netherlands.