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THEME

Gas solubility in Oil-based Mud and it's effect on kick detection: NZ19 case.

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Dedication

To the soul of our mate Sakli Bessaad who left us with huge loss.

To our beloved Mothers and Fathers, source of love and support, Brothers and Sisters, friends and classmates, to our entire families and everyone who helped us to become who we are now, we have crossed a way together, this research is for you!!

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First of all I would like to thank Allah our lord who gave us knowledge and strength to be able to complete our thesis.

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Abstract

SONATRACH as the largest petroleum company in Algeria and Africa, it has moved to explore unconventional recourses, in order to increase proven oil & gas reserves. SONATRACH has started a new project of tight & shale gas, deep water exploration and also exploration in north Algeria. In these areas the risk and the cost are rising up, SONATRACH has to drill more deep and complex wells in these challenging areas where the risk of kicks and blowouts are commonly existing, wich can lead to catastrophic consequences.

As a part of our master's degree research in the drilling engineering department at University of Kasdi Merbah Ouargla, we have conducted a study of gas behaviours and its effects on kicks prevention in the concept of well control modeling & simulation which is necessary in oil & gas industry, where the kicks represent one of the biggest issues since it can lead to well integrity failure resulting human life loss, environment and equipment damage. However, extensive studies have been conducted on modeling and simulation of kicks behavior. These models are a valuable tool for well design, the evaluation of well control procedures and also for rig personnel training since personal can be trained on a simulator and not on real wells.

In this study, we carried out an extensive review of historical kick events in SONATRACH Company from 2009 to 2012. This study provides the context of the importance of well control modeling and simulation. Some of the common existing well control models in open literature are presented. In this case study, most of the simulation runs are based on the well NZ19, this simulation was realized by a commercial software Drillbench© to study the effect of different parameters on the solubility of gas in the drilling fluids and the wellbore pressure.

In the simulation results: we summarized the influence of several factors on the solubility of gas in the drilling fluids and the wellbore pressure. We have noticed that if all parameters that they contribute to the successful completion of wells will be optimized, it certainly many incidents can be avoided during operations.

Key Words: Well control, Blowout, modeling and simulation, single phase, two phase.

ملخص

تعتبر سوناطراك من أكبر شركات البترول في الجزائر و أفريقيا، تتجه إلى استكشاف الموارد غير التقليدية، من أجل زيادة احتياطات النفط والغاز. بدأت سوناطراك مشروعا جديدا للغاز الصخري و البترول والتنقيب في المياه العميقة، وكذلك التنقيب في الساحل الجزائري. في هذه المنطقة التي يكثر فيها خطر الرفسات و الإنفجارات، التي يمكن أن تؤدي إلى نتائج كارثية.

كجزء من مشروع التخرج من كلية الهندسة البترولية تخصص تنقيب بجامعة قاصدي مرباح ورقلة، أجرينا هذه الدراسة لنمذجة ومحاكاة مراقبة الآبار. ان الوقاية من خطر الرفسات و الإنفجارات ضروري في صناعات النفط والغاز، وذلك لأن الرفسات والانفجارات تمثل واحدة من اكبر التحديات في هذا الميدان لأنها يمكن أن تؤدي إلى الفشل في سلامة البئر مما يؤدي لخسائر بشرية، وأضرار بيئية وفقدان للمعدات. ومع ذلك تم إجراء دراسات مستفيضة على نمذجة ومحاكاة سلوك الرفسات. تعتبر هذه النماذج أداة قيمة لتصميم الآبار، وتقييم إجراءات الرقابة بشكل جيد وأيضا لتدريب الموظفين نظرا لإمكانية التدريب عن طريق المحاكاة و ليس على بئر حقيقي.

في هذه الدراسة، أجرينا مراجعة تاريخية شاملة لأحداث رفسات الآبار في شركة سوناطراك من عام 2009 إلى عام 2012. يدل هذا السياق على أهمية نمذجة ومحاكاة مراقبة الآبار بشكل جيد. يتم عرض بعض نماذج التحكم الجيدة الموجودة في الأبحاث العلمية. في دراسة الحالة هذه، تعتمد معظم عمليات المحاكاة على البئر 19نزلة ، وقد تم تحقيق هذه المحاكاة بواسطة برنامج تجاري لدراسة تأثير المتغيرات المختلفة على قابلية انحلال الغاز في سوائل الحفر و ضغط البئر.

في نتائج المحاكاة، لقد استخلصنا التأثير الذي تقوم به عدة عوامل على قابلية انحلال الغاز في سوائل الحفر وضغط حفرة البئر. حيث لاحظنا أنه إدا تم تحسين المتغيرات التي تساهم في نجاح إكمال البئر ،ستمكن من تجنب المخاطر أثناء العمليات.

الكلمات المفتاحية : مراقبة الآبار، الرفسات و الإنفجارات ، النمذجة والمحاكاة، أحادي الطور، ثنائي الطور.

Resumé

Sonatrach en tant que leader africain dans le secteur pétrolier est actuellement menée à l'exploitation des réserves non conventionnelle afin d'augmenter ses réserves prouvées pour répondre à la demande de la consommation énergétique mondiale qui ne cesse à croître. Pour cela, Sonatrach a lancé des grands projets d'exploration des tight & shale gaz et au nord de l'Algérie onshore et offshore ce qui implique l'activité de forage à réaliser des puits de plus en plus profonds et complexes. Dans cette conjoncture le risque des venues et des éruptions est omniprésent, qui est évalué au potentiel du désastre.

Dans le cadre de notre formation Master en forage pétrolier au sein de l'université de Kasdi Merbah Ouargla, nous avons réalisé cette étude sur l'effet de la solubilité des gas dans le concepte de modélisation et la simulation des venues. La prévention des venues est primordiale dans le forage pétrolier car la majorité des venues ont aboutie à un échec de control, qui a donné des éruptions causant des dommages inestimables. Cependant des études poussées ont été réalisées sur la modélisation et la simulation du comportement des venues. Ces modèles font un outil précieux pour le désigne du puits, l'évaluation des procédures de contrôle et également pour la formation du personnel, car on peut s'entrainer sur un simulateur mais pas sur un vrais puits.

Dans cette étude, nous avons commencé par étude statistique des venues enregistrées à la SONATRACH de 2009 à 2012. Cette étude met en évidence l'importance de la modélisation et de la simulation du contrôle de puits. Certains des modèles de contrôle de puits existants dans la littérature sont présentés. Dans cette étude de cas, la plupart des simulations sont basées sur le puits NZ19. Cette simulation a été réalisée par un logiciel commercial, Drillbench ©, pour étudier l'effet de différents paramètres sur la solubilité du gaz dans les fluides de forage et la pression des puits.

Dans les résultats de simulation, nous avons résumé l'influence de différents facteurs sur la solubilité des gaz et la pression de puits. Nous avons constaté que si tous les paramètres qu'ils contribuent à la complétion de puits sont bien optimisés, plusieurs incidents seront évités pendant les opérations.

Mots Clés : Well control, éruption, modélisation et simulation, single phase, two phase.

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Nomenclature

AGH : Annular gas head bar

ALH_i : annular hydrostatic pressure of the liquid at iteration i bar

C_{AN} : annular capacity litre/m

CP : Casing pressure bar

FP : Formation pressure bar

h_g : Hauteur du gaz m

i : Iteration number

P_i Pressure at iteration i bar

p_{MP} : Pressure in the middle of Gas/ Mud bar

p_{pc}: pseudo-critical pressure bar

P_{pr}: pseudo-reduced pressure bar

SICP= annular pressure at shutting the well bar

T_i : Temperature at iteration i °R

T_{pc}: Pseudo-critical temperature °R

T_{pr}: Pseudo-reduced temperature °R

V_A : annular volume Litre

V_C : circulated volume Litre

V_{Cmax} : circulated volume (gas on surface) litre

V_{DP}= interior volume of drill string Litre

V_i= volume at iteration i Litre

V_T= Total volume of well Litre

Z : Compressibilty factor

d_g : Gas densty s.g

$(\frac{dp}{dx})_{ODM}$=the pressure gradient of initial mud bar/m

$(\frac{dp}{dx})_{KM}$= Pressure gradient of mud of the required density bar/m

g_{hydr} : Hydrostatic gradient

g_{fric} : The friction gradient for the power model

g_{acc} : the acceleration gradient

Δp_1=The pressure variation due to the mud of the required density present in the annular space bar

Δp_2=Pressure variation due to volume expansion bar

Δp_3: Pressure vartiation due to gas evacuation bar

Abbreviation

HMD: Hassi Messouad Field

NZ19: Nezla well 19

s.g: Specific gravity

SPM: Strokes per Minute

BOP – Blowout Preventer

BHA – Bottom Hole Assembly

BHP – Bottom Hole Pressure

EOS – Equation of State

GOR – Gas-Oil Ratio

HPHT – High Pressure, High Temperature

MPD – Managed Pressure Drilling

OBM – Oil-Based Mud

OWR – Oil-Water Ratio

PVT – Pressure-Volume-Temperature

ROP – Rate of Penteration

SICP – Shut-In Casing Pressure

SIDPP – Shut-In Drill Pipe Pressure

WBM – Water-Based Mud

WOB – Weight on Bit

Chapter01: General Introduction

Introduction:

Drilling engineering is often facing technical challenges related to the crossing of deep formations that contain fluids under certain abnormally high pressures that could endanger human life, the environment and equipment. The evolution of the oil and gas industry towards the exploitation of unconventional resources implies the drilling activity to realize increasingly deep and complex wells. In this conjuncture the risk of kicks or eruptions is omnipresent, valued as a potential of a disaster.

To access to the energy resources of the subsoil s one in a safe manner is one of the major challenges in oil and gas industry. For this, large-scale projects were made in place to improve safety and ensure the integrity of boreholes while they focus on projects development of oil companies and drilling operators. The main focus of these projects is the most realistic simulation of the well control and the fabrication of the representative drill simulators of a drilling site, to avoid kicks in wellbore or at least control them by a well-studied drill program, a good choice of drilling rig and kicks control equipment, well-adapted drilling procedures, and a qualified drilling team.

The control of the kick depends essentially on the competencies and the reactivity of the drilling team, which can only be realized by training the personnel on a drilling simulator and most representative of the real situations on a drilling site.

1.1. Objectives:

The principal objectives of the study are:

- The presentation of the principal mathematical equations of the kick control.
- To show the interest of the simulation on well control at the different stages of drilling operation realization .
- The evaluation of different parameters that affect the gas solubility and the wellbore pressure.

1.2. Methodology:

The methodology followed to achieve the objectives of this study is as follows:

- Collection and analysis of kick data encountered at SONATRACH between 2009 and 2012.
- Bibliographic research on kicks modeling.

- A two phase dynamic well control commercial software that is used to investigate the factors that affect gas solubility and the wellbore pressure in a closed drilled well with water or oil based drilling fluids.
- Analysis and discussion of simulation results.

1.3. The structure of the study:

The structure of the study is as follows:

- **Chapter01:** General Introduction.
- **Chapter02:** Presentation of a statistical study of kicks recorded at SONATRACH between 2009 and 2012 by the well control unit of the engineering department at the drilling division.
- **Chapter03:** This chapter is devoted to present the main mathematical equations that are used in well control, the two-phase model, the detail of the single-phase model and the Rheology model.
- **Chapter04:** This chapter is devoted to the literature of the gas solubility, factors that are affecting solubility, Consequences of as dissolution and PVT models.
- **Chapter05:** In this chapter we present the tools used for the simulations, and the configuration of the NZ19 well which is used for the case study as well as the different simulation scenarios. The results and discussion of the simulations are presented in this chapter also.
- **Chapter06:** As a last chapter, we end up with a conclusion and a list of recommendations to the case we have studied.

Chapter 02: SONATRACH Kick's history

Introduction:

In the meantime, Kicks and eruptions are not often indexed and analyzed. However, in the recent years, any kick or eruption is systematically listed and analyzed to ensure well integrity. In this perspective, the Drilling Division of SONATRACH created the Well Control cell within the engineering department to strengthen teams and contribute to it's QHSE initiative on the drilling fields. As part of its missions, the Well Control cell carried out a statistical study of kicks that took place in SONATRACH fields between 2009 and 2012. The criteria of this study are the causes, the type of kicks, the field, the device and the operations in progress. The objective of this study is to analyse the main causes of the kicks in order to improve the preventive procedures and also the methods and the tools of control to reduce the number of kicks.

Nowadays, the majority of kicks that took place on the Sonatrach's fields, are classified at the beginning of the third category of control, hence the training of supervisors on the third category is needed.

2.1. Kicks according to the activity:

The below results show the activity of drilling division for the period 2009 to 2012, 396 wells were recorded during this period, where 34 Kicks recorded. This has given an average frequency of 8,85%, in other words 8,85 Kicks for 100 wells drilled.

Another results show that from 2010 the number of kicks has a tendency decreasing while that of the number of wells drilled is increasing. The frequency of kicks from 16.44% in 2009 to 4% in 2012, while the number of wells has increased from 73 wells in 2009 to 163 wells in 2011 and then dropped to 50 wells in 2012. This shows that the kick is not a probabilistic event that depends on the number of wells drilled, but a defined event that occurs if the necessary conditions are met independently of the number of completed wells. [27]

However if all the parameters that contribute in the well realization depend on the drilling program, the drilling rig, the monitoring equipement, the control equipement, the human resources, and the accurate procedures are ensured and gathered, a large number of incidents can avoided.

This shows the tremendous efforts that were made by the Well Control cell engineering department to improve the preventive measures, conducted in 2009.

Table 2-1: Drilling activity per years

Years	Wells	Kicks	Frequency
2009	73	12	16,44%
2010	110	13	11,82%
2011	163	7	4,29%
2012	50	2	4%

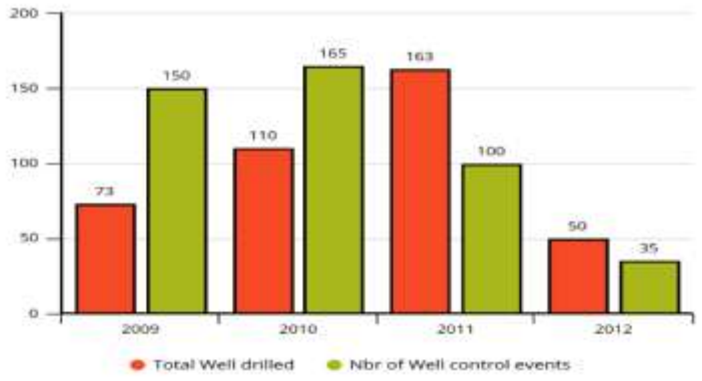


Figure 2-1: Number of kicks compared to drilled wells

2.2. Kicks depending on operations:

During these four years of kicks studies, encountered ongoing drilling operations are the most prevalent, and represent 41.17% of cases.

Follow-up of kicks during the tripping operations by a rate of 38.23% of cases. The number of kicks during special operations (logging, ballooning, DST and completion) is relatively low.

During drilling and Tripping operations, the kicks rate is 79.4%, this indicates that the operator and the drilling contractor have failed to maintain the first safety barrier that is the hydrostatic pressure of the mud. The causes of this failure are :

- The density of the mud is insufficient.

- The swabbing is resulting a loss of the safety margin .

Table 2-2: Number of kicks per operations.

Operations	Kicks	Frequency
Drilling	14	41,17%
Tripping and coring	13	38,32%
Logging /perforation	1	2,94%
Ballooning	3	8,83%
DST	1	2,94%
Production	1	2,94%
Completion	1	2,94%
Total	34	100%

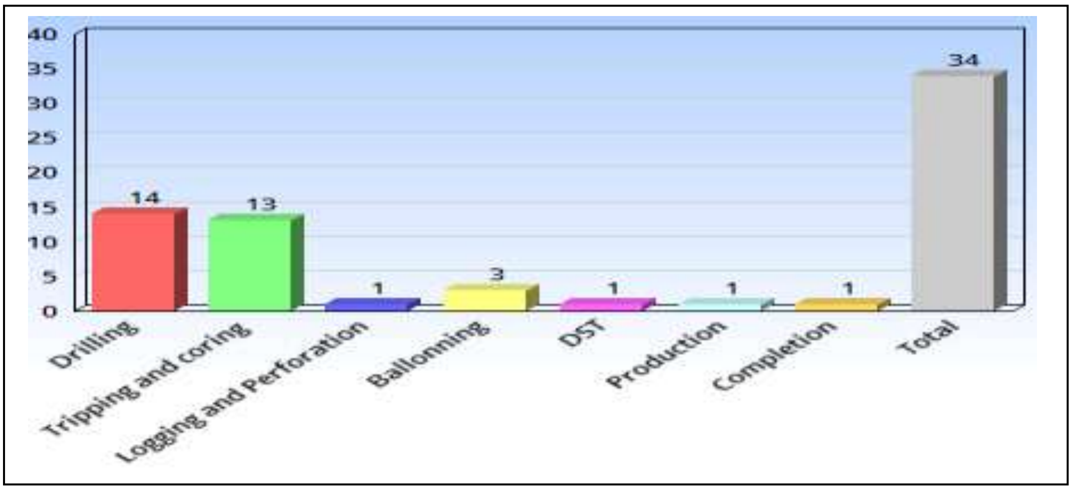


Figure 2-2: Number of kicks function to operations

2.3. Kicks according to the type:

The classification of the Kicks by type is made on the basis of the difference between the pressure hydrostatic mud and that of the reservoir. They are subdivided into 3 types. [27]

Induced kicks:

This type characterizes the kicks caused by the loss of the first safety barrier, which is the hydrostatic pressure of the mud, the main causes of this type of kicks are:

- Improper hole fill up.

- Swabbing.
- Decrease of the mud density.
- Lost circulation.

Table 2-3 shows that the induced kicks are the most prevalent and represent 37% of cases.

Underbalanced kicks:

This type characterizes the kicks that took place during Drilling and coring operations in permeable zone with insufficient mud density. Here the rate of kicks represents 34% of case. This problem is generally encountered in exploration regions where the pressure of reservoir is not well known or poorly estimated.

Other type:

This type characterizes the kicks encountered during special operations such as DST, back flow, ballooning effect, unsuitable or unidentified well shut.

Table 2-3: Kick types

Kick type	Number of kick	Frequency
Induced	13	37%
Underbalanced	12	34%
Other	9	9,26%

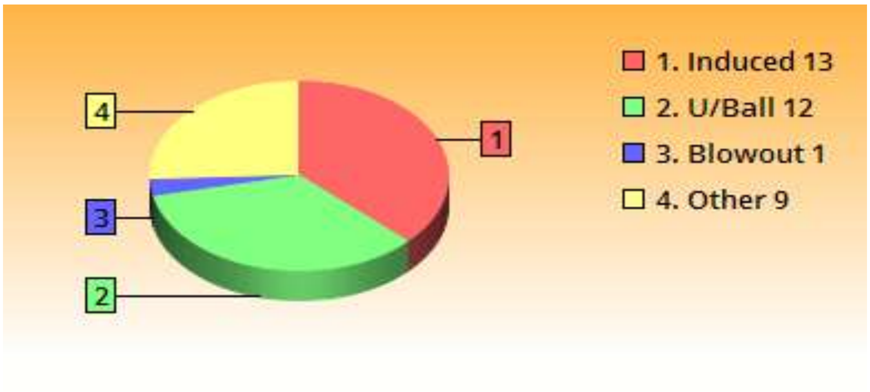


Figure 2-3 : Kicks type

2.4. Kicks according to the field:

Table 2-4 shows the number of kicks by field name.

Field name	HMD OM	HMD DM	BRIDES	NEZLA	IN AMINAS	IN SALAH	AHNET	HASSI R'mel	BERkaoui
Number	8	6	1	3	4	4	5	1	3

Figure 2-4: kicks function to the fields

We found that that 14 kicks were encountered in the Hassi Messoud field which represents a rate of 41,17%. It is noted that the first drilling on the HMD field was carried out in 1956.It shows how the field of Hassi Messaoud is complex and heterogeneous. The difficulties associated with drilling in the Hassi Messaoud field have made it a school and a world reference in oil exploitation. [27]

Chapter03: Presentation of mathematical equations of the kicks

Introduction:

Simulation is still the most efficient tool for performance studies, optimization, risk and environmental impact of different systems. In drilling engineering, the modeling of the behavior of the well under control of a coming is fundamental to better understand the variation of annular pressures as well as the effect parameters that influence them. Several models of comings have been developed, in the objective of better mastering the arrivals, for offshore and onshore wells. These models are classified in two groups: single phase models and two phase models. This chapter is devoted to the presentation of the main existing models of Kick .The single phase model of LeBlanc and Lewis as well as the two phase models of Santos, Nickens and Jonggeum,Hassan and Kabir and that of Choe and Juvakam-Wold are presented.

3.1.Single phase model

3.1.1.Summary of the Single Phase model:

In 1968, Le Blanc and Lewis proposed the first mathematical model of a circulating gas using conventional control methods, which are: Driller's and Wait and Weight methods. The model assumes that the volume of gas kick entering the well is known and behaves as a single phase throughout its circulation from the bottom to the surface, taking in consideration the effect of volume expansion, with both methods, Driller's and Wait and Weight methods. During the circulation, the pressure at the bottom of the well is kept constant. For reasons of simplicity, some parameters are neglected in this model,[12]

based on:

- The gas migration speed.
- Pressure drop.
- The sliding speed of the gas with respect to the liquid (mud).
- The variation of the annular geometry.
- The solubility of the gas in the mud.

Following these hypotheses, the results of the model do not represent the reality of the phenomenon but informs on the trend and behavior of the kick.

3.1.2.Single phase model equations:

The variation of the annulus pressure depends mainly on the volume expansion of the gas plug (kick) and the hydrostatic pressure prevailing in the well.

In this model, the bottom hole pressure equals to the pressure of the formation and stills constant throughout the circulation of the kick, this allowed the determination of the annulus pressure by subtraction of the hydrostatic pressure from the formation pressure. Therefore the annulus pressure can be expressed by:

Casing pressure (CP) =Formation pressure (FP) – Liquid hydrostatic pressure – Annulus gas head (AGH) ……………………………. (1)

The circulation of the kick is subdivided into four main phases. The description and the equations governing these phases are presented as the following: [12]

Phase 1: displacement in the drill string:

This phase describes the movement of the initial drilling mud through the required density sludge from the surface to the bottom of the well. Here the variation of the annulus pressure is affected only by the volume expansion of the inlet, which decreases the hydrostatic pressure and increases the annulus pressure.

The variation of the hydrostatic pressure is given by:

$$ALH_i = \left[\frac{V_A - V_i}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{ODM}\right] \quad V_c \leq V_{c_{max}} \quad \text{……………………………. (2)}$$

Where:

ALH_i = Annulus hydrostatic pressure of the liquid at iteration i.

V_A ,V_C and V_{Cmax} = Annulus volume, Circulated Volume, Circulated Volume (gas on surface).

V_i = Volume at iteration i.

C_{AN} = Annulus capacity.

$(\frac{dp}{dx})_{ODM}$ = Pressure gradient of initial mud.

The law of behavior of the gas plug of Boyle and Charle is used in this model. This law allowed the determination of the volume of the gas under various conditions of pressure and temperature, expressed by:

$$V_i = V_{i=1}\left[\frac{P_{i=1}}{P_i}\right]\left[\frac{T_i}{T_{i=1}}\right]\left[\frac{Z_i}{z_{i=1}}\right] \quad V_c \leq V_{c_{max}} \quad \text{…..……………….………. (3)}$$

Where:

P_i ,T_i and Z_i = Pressure, Temperature, and Compressibility factor at iteration i.

The substitution of equation 3.2 in equation 3.1 gives the annular pressure equation for phase 1 in the following form:

$$CP = SICP + \left[\frac{V_i - V_1}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{ODM}\right] \quad V_c \le V_{dP} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where:

SICP= annular pressure at shutting the well

V_{DP}= interior volume of drill string

Phase 2: Intermediate displacement

At the arrival of mud of the required density in the annular space, the hydrostatic pressure of the liquid phase contained in the annular space changes its value, the variations thereof being expressed by:

$$(\Delta p)_1 = \left[\frac{V_c - V_{dp}}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{KM} - \left(\frac{dp}{dx}\right)_{ODM}\right] \quad V_{dp} < V_c \le V_T \qquad \ldots\ldots\ldots\ldots (5)$$

$$(\Delta p)_{2i} = \left[\frac{V_i - V_1}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{ODM}\right] \quad V_c \le V_{c_{max}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The substitution of equations 3.5 and 3.6 in the equation for the initial hydrostatic pressure of the liquid phase 3.2 gives the new equation of hydrostatic pressure of the liquid phase in the following form:

$$ALH_i = ALH_{i=1} + \Delta p_1 - \Delta p_2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where:

Δp_1=The pressure variation due to the mud of the required density present in the annular space.

Δp_2=Pressure variation due to volume expansion

$(\frac{dp}{dx})_{KM}$= Pressure gradient of mud of the required density.

V_T= Total volume of well.

The substitution of equation 3.7 in equation 3.1 gives the annular pressure for phase 2 in the following form:

$$CP = SICP - \left[\frac{V_c - V_{dp}}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{KM} - \left(\frac{dp}{dx}\right)_{ODM}\right] + \left[\frac{V_i - V_1}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{ODM}\right] \quad V_{dP} < V_c \le V_{c\max} \qquad \text{……….. (8)}$$

Phase 3: Surface gas arrival:

This phase is initiated by the arrival of the gas on the surface (chock line). The hydrostatic pressure of the liquid phase and the pressure in the base of the gas cap vary with the production of the gas.

The variation of the hydrostatic pressure of the liquid phase following the reduction of the volume of gas can be expressed by:

$$(\Delta p)_3 = \left[\frac{V_A - V_c - V_1}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{ODM}\right] \quad V_{c\max} \le V_c < V_A \qquad \text{………………....……(9)}$$

The substitution of equations 3.5 and 3.9 in the equation for the initial hydrostatic pressure of the liquid phase 3.2 gives the new equation of the hydrostatic pressure of the liquid phase in the following form:

$ALH_i = ALH_{i=1} + \Delta p_1 - \Delta p_3 \quad V_{Cmax} \le V_C < V_A$

With gas production, the pressure variation at the base of the gas cap can be expressed by:

$$AGH = \frac{0.001293\gamma_g p_{MP} h_g}{ZT} \quad V_{c\max} \le V_c < V_A \qquad \text{……………………. (10)}$$

Where:

d_g : gas density (sg)

p_{MP} : Pressure in the middle of the gas plug

h_g : gas height

The substitution of equations 3.10 and 3.11 in equation 3.1 gives the annular pressure for phase 3 in the following form:

$$CP = FP - ALH_1 - \left[\frac{V_c - V_{dp}}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{KM} - \left(\frac{dp}{dx}\right)_{ODM}\right] + \left[\frac{V_A - V_c - V_1}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{ODM}\right] - \frac{0.01875\gamma_g p_{MP} h_g}{ZT} \qquad \text{…….. (11)}$$

Phase 4: End of circulation

This last phase is initiated by the total evacuation of the gas (kick) and continues until the arrival of the mud of density required on the surface. During this phase the annular pressure decreases while the hydrostatic pressure of the liquid phase increases.

The hydrostatic pressure of the liquid phase is given by:

$ALH_i = ALH_{i=1} + \Delta p_1$ ………………………….. (12)

The substitution of equations 3.13 in equation 3.1 gives the annular pressure for phase 4 in the following form:

$$CP = FP - ALH_1 - \left[\frac{V_c - V_{dp}}{C_{AN}}\right]\left[\left(\frac{dp}{dx}\right)_{KM} - \left(\frac{dp}{dx}\right)_{ODM}\right] \quad V_A \le V_c \le V_T \qquad \text{……(13)}$$

Calculation of the compressibility factor:

The compressibility factor of the real gases is determined by an empirical formula using the pseudo-reduced parameters of the gas, namely the pseudo-reduced pressure and the pseudo-reduced temperature expressed by:

$$p_{pr} = \frac{p}{p_{pc}} \quad \text{and} \quad T_{pr} = \frac{T}{T_{pc}} \qquad \text{…………………………(14)}$$

Where:

P_{pr} and T_{pr} are respectively the pseudo-reduced pressure and temperature, p_{pc} and T_{pc} are respectively the pseudo-critical pressure and temperature, which are estimated by the Charts correlation for real gases:

$$p_{pc} = 48.41 - 3.44\gamma_g \quad \text{and} \quad T_{pc} = 213.5 + 245\gamma_g .$$

The correlation of the compressibility factor is given by:

$$z = \frac{0.55452 - \log T_{pr}}{5.1886} p_{pr} + \frac{\log T_{pr} + 0.00963}{0.47273} p_{pr} \qquad \text{……..……………(15)}$$

3.2. Two phase models:

3.2.1. Santos model:

Santos proposed in 1991 a mathematical model for deep-water wells. This model takes into account the following parameters:

- The sliding speed between the gas and the mud.
- The Void fraction parameter.
- Pressure drop using the Orkiszewski correlation.
- The rheological model of the mud is power law model.
- The type of flow is Bubbles flow.

This study shows that the volume of gain and the density of the effluent have a dominant effect on the profile of the annular pressure during the circulation of the kick. On the other hand, the effects of well geometry, void fraction, water depth (offshore wells) and mud rheology has a relatively small effect on ring pressure during gas flow.

Subsequently, this model has been developed to be valid for horizontal wells and the kicks during tripping. This latest study shows that kick tolerance is higher in horizontal wells than vertical wells.

The main limitations of the Santos model are: Well geometry is assumed to be constant and the initial void fraction parameter is calculated without taking into account the parameters of the formation. [17]

Santos's model equations:

Three regions can be observed during the flow of the kick, the first is a monophasic region contains drilling mud; the second phase is a biphasic region contains a mixture of gas and drilling mud so the third is a monophasic region contains gas located above the first and second region.The losses of loads in the regions are given by the following relations:

Region3:

$\Delta p_3 = g_{hydr}\ TVD + g_{fric}\ MD$ …………………………(1)

Region1:

$\Delta p_1 = g_{hydr}\ TVD + (g_{fric} + g_{acc}) MD$ …………………………(2)

Where:

g_{hydr} : Hydrostatic gradient

g_{fric} : The friction gradient for the power model

g_{acc} : the acceleration gradient, calculated by the following relation:

$$g_{acc} = 0.0016 \rho_L \left[(v_{lc} - v_{lp}) / \Delta t \right].$$ …………………………(3)

Region 2:

The pressure drop in this region will be determined by the use of three fundamental equations of fluid mechanics:

1. **Continuity equations:**
   - Liquid phase:

$$\frac{\partial y}{\partial t} + \left[\frac{\partial y v_L}{\partial x} \right] = 0.$$ …………………………(4)

- Gas phase:

$$\frac{\partial\left[(1-y)\rho_g\right]}{\partial t}+\left[\frac{\partial\left[(1-y)v_g\rho_g\right]}{\partial x}\right]=0 \qquad \text{..............................(5)}$$

2. Balance of momentum:

$$0.0016\left\{\frac{\partial\left[v_L^2\rho_L y+v_g^2\rho_g(1-y)\right]}{\partial x}\right\}+0.0016\left\{\frac{\partial\left[v_L\rho_L y+v_g\rho_g(1-y)\right]}{\partial t}\right\}+g+g_{fric}+g_{hydr}=0 \qquad \text{......(6)}$$

Where:

g_{fric} and y (hold up of liquid) are estimated by the Beggs-Brill correlation suitable for inclined pipe.

g_{hydr} :Hydrostatic gradient is estimated by:

$$g_{hydr}=0.052\left[y\rho_L+(1-y)\rho_g\right]\cos\alpha \qquad \text{........................(7)}$$

3. State equation:

$$\rho_g=0.361\frac{\gamma_g P}{TZ}. \qquad \text{........................(8)}$$

The set of nonlinear equations obtained depends on five parameters: the pressure, the velocity of gas and liquid, the density, the liquid holdup and which in turn depend on time and position. The numerical resolution of these equations is essential, for that we propose the method of the finite differences like tool of resolution thanks to its simplicity of implementation in this type of problem.

1. Continuity equation :

- Liquid phase:

$$(1-F_w)\left[(v_L y)_2-(v_L y)_1\right]+F_w\left[(v_L y)_4-(v_L y)_3\right]+\left(\frac{\Delta x}{2\Delta t}\right)(y_3+y_4-y_1-y_2)=0. \qquad \text{...............(9)}$$

- Gas phase:

$$(1-F_w)\left\{\left[(v_g(1-y)\rho_g\right]_2-\left[(v_g(1-y)\rho_g\right]_1\right\}+F_w\left\{\left[(v_g(1-y)\rho_g\right]_4-\left[(v_g(1-y)\rho_g\right]_3\right\}$$
$$+\left(\frac{\Delta x}{2\Delta t}\right)\left\{\left[(1-y)\rho_g\right]_3+\left[(1-y)\rho_g\right]_4-\left[(1-y)\rho_g\right]_1-\left[(1-y)\rho_g\right]_2\right\}=0......(10) \qquad \text{......(10)}$$

2. **Momentum balance for the mixture:**

$$\left(\frac{0.0016}{2\Delta x}\right)\left\{\begin{matrix}\left[v_g^2(1-y)\rho_g\right]_2+\left[v_g^2(1-y)\rho_g\right]_4-\left[v_g^2(1-y)\rho_g\right]_1-\left[v_g^2(1-y)\rho_g\right]_3\\+(v_L^2 y\rho_L)_2+(v_L^2 y\rho_L)_4-(v_L^2 y\rho_L)_1-(v_L^2 y\rho_L)_3\end{matrix}\right\}+$$

$$\left(\frac{0.0016}{2\Delta t}\right)\left\{\begin{matrix}\left[v_g(1-y)\rho_g\right]_3+\left[v_g(1-y)\rho_g\right]_4-\left[v_g(1-y)\rho_g\right]_1-\left[v_g(1-y)\rho_g\right]_2\\+(v_L y\rho_L)_3+(v_L y\rho_L)_4-(v_L y\rho_L)_1-(v_L y\rho_L)_2\end{matrix}\right\}+$$

$$\frac{(p_3-p_4)}{\Delta x}+0.25(g_1+g_2+g_3+g_4)_{fric}+0.25(g_1+g_2+g_3+g_4)_{hydr}=0... \quad ....(11)$$

Where:

F_w: ratio of bubble volume on fluid volume

- Continuity equation: F_w =1 for the implicit scheme (continuity equation) ,F_w =0,5 for the centered scheme.
- Momentum balance

Δx, Δt : No mesh of space and time, respectively

- point 1: represents the fluid properties at the system exit at t -Δt
- point 2: represents the fluid properties at the system inlet at t -Δt
- point 3: represents the fluid properties at the system output at t
- point 4: represents the fluid properties at the system input at t

The figure below illustrates the discretization of the system:

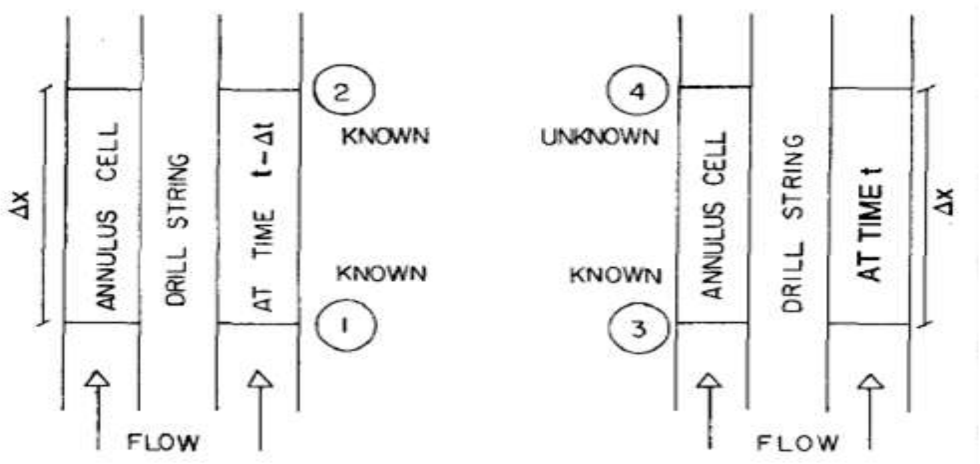


Figure 3-1: finite difference scheme in annular space

The properties of the flow are known at points 1,2,3. The previous finite difference scheme is used to calculate the properties of the fluid at point 4 and using these properties we can calculate the pressure loss in each region as a function of time and the distance x.

3.2.2.Nickens model:

The Nickens model, developed in 1987, is obtained by solving the transient mass conservation equations of the two phases, drilling mud and gas, separately. The momentum conservation equation is used for the two-phase mud-gas region, in this equation the parameters of the two phases have been combined to have the equivalent parameters of the mud-gas mixture, these parameters are void fraction, density, velocity, pressure and temperature. The sliding speed of the gas with respect to the drilling mud, in two-phase mud-gas region, is obtained from the correlations. The possible types of flow in the two-phase mud-gas zone are three: distributed bubble pattern, fully developed slug pattern and transition pattern.

This model takes into account the variation of the well geometry and the pressure drops and allows the estimation of the ring pressure, in the offshore wells, during the circulation of the arrivals with the two methods of circulation, Driller's and Wait and Weight methods. It is noted that in this model the explanation of the effect of the various parameters on the distribution of the gas in the ring, necessary for the determination of the type of flow, has not been addressed.

The comparison of the real results of a circulation of a visit with those obtained with the model of Nickens shows that the results are very close. [16]

Nickens model equations:

The equations used by Nickens are

1. **Continuity equation**
   - Drilling fluid:

$$\frac{\partial}{\partial t}\left[\rho_m(1-\lambda)\right]+\frac{\partial}{\partial z}\left[\rho_m v_m(1-\lambda)\right]=0.............(1)$$

   - Gas phase

$$\frac{\partial}{\partial t}(\rho_g\lambda)+\frac{\partial}{\partial z}(\rho_g v_g\lambda)=0.............(2)$$

2. **Momentum balance of the mixture:**

$$\frac{\partial}{\partial t}\left[\rho_m v_m(1-\lambda)+\rho_g v_g\lambda\right]+\frac{\partial}{\partial z}\left[\rho_m v_m{}^2(1-\lambda)+\rho_g v_g{}^2\lambda\right]+$$
$$\frac{\partial p}{\partial z}+\left(\frac{\partial p}{\partial z}\right)_f+\left[\rho_m(1-\lambda)+\rho_g\lambda\right]g=0.............(3)$$

3. Empirical correlation for calculating gas velocity:

$$v_g = K_g\left[v_m(1-\lambda)+v_g\lambda\right]+v_{gs}(\rho_g,\rho_m,\lambda,\sigma,d_e,d_i)\text{.......}(4)$$

4. State equation:

- Drilling fluid:

$$\rho_m = \rho_m(T,P)\text{..........}(5)$$

- Gas:

$$\rho_g = \rho_g(T,P)\text{...........}(6)$$

5. Viscosity:

- Drilling fluid: considered constant
- Gas: calculated by Lee et al correlation
- Mixture: calculated by

$$\mu_M = \mu_g\lambda + \mu_p(1-\lambda)$$

6. Density:

- Drilling fluid: estimated by adjusting the density of mud at surface.
- Gas: calculated by state equation of Redlich-Kwong.
- Mixture: calculated by

$$\rho_g\lambda + \rho_m(1-\lambda)$$

7. Pressure drop:

- Monophasic: the calculation of the pressure drop in the case of the flow of the drilling mud is given by the following relation:

$$\left(\frac{\Delta p}{\Delta z}\right)_f = (0.8066*10^{-3})\frac{f\rho_m v_m^2}{d_H}\text{...........}(7)$$

We use the correlation of Blasius for the calculation of friction factor f in the case of a power model of rheology

1. Laminar flow

$$f = \frac{64}{N_{\text{Re}}}, N_{\text{Re}} < N_{\text{Re}l} = 3,470-1,370n.$$

2. Turbulent flow

$$f = aN_{\mathrm{Re}}^{-b}, N_{\mathrm{Re}} > N_{\mathrm{Re}T} = 4,270 - 1,370n.$$

Where:

$$a = [\log(n) + 3.93]/12.5$$
$$b = [1.75 - \log(n)]/7$$
$$n = 3.32\log[(\sigma_{yp} + 2\mu_p)/(\sigma_{yp} + \mu_p)]$$
$$k = [(\sigma_{yp} + 2\mu_p)k']/[100(1,022)^n]$$
$$k' = [(2n+1)/2n]^n \ annulus$$
$$k' = [(3n+1)/4n]^n \ pipe$$
$$N_{\mathrm{Re}} = [0.23v_m^{(2-n)}d_H^n\rho_m]/k(8)^{n-1}$$

For the transition zone the friction factor will be calculated a linear interpolation between the case of turbulent flow and laminar flow.

- Biphasic: in the case of biphasic steady state, the correlation of Beggs and Bril for the calculation of the pressure drop. The void friction factor is given according to the flow configuration and the inclination of the pipe.
- The configurations considered are:

Bubble flow: if the gas fraction is: $\lambda \leq \lambda_t = 0.25$

$$v_{gs} = 1.41\left[\frac{\rho_m^2\sigma g}{(\rho_m - \rho_g)}\right]^{1/4} ; 0 < \lambda < \lambda_t ....(9)$$

Fully developed slug: if the gas fraction was:

$$\lambda > \lambda_{gsl}$$

$$v_{gsl} = 0.55K_g\left[\frac{(d_e + d_i)(\rho_m - \rho_g)}{\rho_m}\right]^{1/2} ;................(10)$$

$$K_g = 1.454 - 0.0273\ln(N_{Re_{gsl}}) - 0.00168\sigma_{yp}^{0.946} and$$

$$N_{Re_{gsl}} = \frac{928 v_{gsl}\rho_m}{\mu_p} and$$

$$\lambda_{gsl} = \max\left[0.4, 0.4 + 5(\lambda_0 - 0.4)/6\right]$$

$$\lambda_0 = \frac{v_{br}}{v_{br} + v_{gsl}} and$$

$$v_{br} = \left[13.2(\rho_m - \rho_g)^{0.56}(d_e - d_i)^{0.69}\right] / (\rho_m^{0.44}\mu_p^{0.12})$$

For the slug flow state in the choke, v_{gsl} is calculated by:

$$v_{gsl} = 1.99\left[(\rho_m - \rho_g)d_i / \rho_m\right]^{0.5}$$

And:

$$\lambda_{gsl} = 0.85$$

Transient flow when void gas fraction . To ensure the continuity of the digital solution, the sliding speed in this area will be estimated by linear interpolation between the two previous areas.

8. Gas flow at kick zone:

$q_g = \sum_{i=0}^{N(t)} q_{gi}$ q_{gi} is the partial gas flow at segment i .

$$q_{gi} = \frac{kh_i\left(p_{fm}^2 - p_{wf}^2\right)}{1{,}424P_D(T\mu Z)_{fm}}$$

Where:

$$p_D = \left[\ln(t_D) + 0.81\right] / 2 and$$

$$t_D = \max\left[10, 7.317(-5)t / r^2(k / \phi\mu c_g)_{fm}\right]$$

h_i is the height of the segment i, obtained by the multiplication of ROP by Δt.

Numeric solution:

The finite difference method is used as a numerical tool for solve the set of equations 1,2,3

- The numerical formulation of mass conservation is:
  Drilling fluid:

$$(1-\alpha)\left[\rho_m v_m(1-\lambda)\right]_z^t+\alpha\left[\rho_m v_m(1-\lambda)\right]_z^{t+\Delta t}-(1-\alpha)\left[\rho_m v_m(1-\lambda)\right]_{z+\Delta z}^t+\alpha\left[\rho_m v_m(1-\lambda)\right]_{z+\Delta z}^{t+\Delta t}=$$
$$\frac{\Delta z}{2\Delta t}\left[\rho_m(1-\lambda)\right]_z^{t+\Delta t}+\left[\rho_m(1-\lambda)\right]_{z+\Delta z}^{t+\Delta t}-\frac{\Delta z}{2\Delta t}\left[\rho_m(1-\lambda)\right]_z^t+\left[\rho_m(1-\lambda)\right]_{z+\Delta z}^t$$

  Gas:

$$(1-\alpha)\left[\rho_g v_g\lambda\right]_z^t+\alpha\left[\rho_g v_g\lambda\right]_z^{t+\Delta t}-(1-\alpha)\left[\rho_g v_g\lambda\right]_{z+\Delta z}^t+\alpha\left[\rho_g v_g\lambda\right]_{z+\Delta z}^{t+\Delta t}=$$
$$\frac{\Delta z}{2\Delta t}\left[\rho_g\lambda\right]_z^{t+\Delta t}+\left[\rho_g\lambda\right]_{z+\Delta z}^{t+\Delta t}-\frac{\Delta z}{2\Delta t}\left[\rho_g\lambda\right]_z^t+\left[\rho_g\lambda\right]_{z+\Delta z}^t$$

- The numerical formulation of the momentum for the drilling mud / gas mixture becomes

$$\left[\rho_m v_m^2(1-\lambda)+\rho_g v_g^2\lambda\right]_z^t+\left[\rho_m v_m^2(1-\lambda)+\rho_g v_g^2\lambda\right]_z^{t+\Delta t}/2-\left[\rho_m v_m^2(1-\lambda)+\rho_g v_g^2\lambda\right]_{z+\Delta z}^t+$$
$$\left[\rho_m v_m^2(1-\lambda)+\rho_g v_g^2\lambda\right]_{z+\Delta z}^{t+\Delta t}/2+(1-\beta)p_z^t+\beta p_z^{t+\Delta t}+(1-\beta)p_{z+\Delta z}^t-\beta p_{z+\Delta z}^{t+\Delta t}-g\Delta z(\rho_M)_z^t+$$
$$(\rho_M)_z^t+(\rho_M)_z^{t+\Delta t}++(\rho_M)_{z+\Delta z}^{t+\Delta t}/4-\Delta z\left[(\frac{\Delta p}{\Delta z})_z^t+(\frac{\Delta p}{\Delta z})_z^{t+\Delta t}+(\frac{\Delta p}{\Delta z})_{z+\Delta z}^t+(\frac{\Delta p}{\Delta z})_{z+\Delta t}^{t+\Delta t}\right]_f/4=$$
$$\frac{\Delta z}{2\Delta t}\left[\rho_m v_m(1-\lambda)+\rho_g v_g\lambda\right]_z^{t+\Delta t}+\left[\rho_m v_m(1-\lambda)+\rho_g v_g\lambda\right]_{z+\Delta z}^{t+\Delta t}-\frac{\Delta z}{2\Delta t}\left[\rho_m v_m(1-\lambda)+\rho_g v_g\lambda\right]_z^t+$$
$$\left[\rho_m v_m(1-\lambda)+\rho_g v_g\lambda\right]_{z+\Delta z}^t$$

  Where:

α is the iteration parameter for mass conservation.

β is the iteration parameter for the momentum.

3.2.3.The two-phase model of Jonggeun Choe and Juvkam-Wold:

Jonggeun Choe and Juvkam-Wold assume that the use of conservation equations of mass and momentum for a two-phase flow invariable geometry is one of the sources of error associated with the Nickens model.Therefore, they proposed another model of control of the comings which takes into account the variation of the geometry of the well in non-permanent flow regime in space annular. [4] [5] [6]

In this model the ordinary parameters of the gas have been replaced by the pseudo-reduced parameters using the Dranchuk and Abukassem equations. Gas distribution, gas slip speed, gas migration speed when the well is closed are calculated with the correlations of Hasan and Kabir. [9]

This model supposes to have three different phases in the annular space, starting from the bottom to the surface: the phase of the mud of required density, the mixed phase mud-gas and the phase of the drilling mud. [5] [6]

This model is valid under the following hypothesis:

- Transient two-phase flow
- Unidimensional flow.
- Water based mud .
- The solubility of the gas in the mud is negligible.
- The compressibility of the water is negligible.
- The temperature gradient is known.
- The drill bit is at the bottom of the well at the time of the kick.

The comparison of this model with the previous ones shows that this model gives the annular pressure with an overestimation before the evacuation of the gas and an underestimation after the evacuation of the gas compared to the previous two phase models.

Two phase model equations:

Five equations are needed to determine unknown parameters, such as gas and mud velocities, fraction of gas bubbles, pressure and density of the kick.

Equation of mass conservation for mud:

$$\frac{\partial}{\partial t}(A\rho_m H_m) + \frac{\partial}{\partial x}(A\rho_m v_m H_m) = 0.........(1)$$

Equation of mass conservation for gas:

$$\frac{\partial}{\partial t}(A\rho_g H_g) + \frac{\partial}{\partial x}(A\rho_g v_g H_g) = 0.........(2)$$

Linear equation of momentum for the gas / mud mixture:

$$\frac{\partial}{\partial t}\left[A(\rho_m v_m H_m + \rho_g v_g H_g)\right] + \frac{\partial}{\partial x}\left[A(\rho_m v_m^2 H_m + \rho_g v_g^2 H_g)\right]$$
$$+A\frac{\partial p}{\partial x} + A\frac{\partial p_f}{\partial x} + A(\rho_m H_m + \rho_g H_g)g = 0............................(3)$$

The correlation to calculate the gas velocity in the mixture:

$$v_g = f(v_m, v_g, \theta, d_o, d_i, \sigma, p, T)..............(4)$$

State equation to calculate gas velocity:

$$\rho_g = 3.488 \frac{\gamma_g p}{zT} \dots\dots\dots\dots\dots\dots(5)$$

The single phase is characterized by gas void fraction equals to zero, it can be found inside the drill string and at the annular. In this phase, the total pressure gradient (hydrostatic pressure and pressure drop) can be calculated from the following equation:

$$\frac{\Delta p}{\Delta L} = 980\rho + \frac{\Delta p_f}{\Delta L} + \rho \frac{v^{n+1} - v^{n+1}}{\Delta t} \dots\dots\dots(6)$$

The steps of the calculation and the solution:

The calculations for this model are divided into three steps:

Step1: drilling until gas detection

The kick is detected by observing a gain of drilling mud; the gas inflow rate is obtained by assuming infinte- acting homogeneous reservoir with skin.

Step2: Pump off and shut in

The amount of pressure build-up for the given duration is calculated from:

$$p^{n+1} = p^n \frac{z^{n+1} n^{n+1}}{z^n n^n} \dots\dots\dots(7)$$

Where:

n is the number of moles of gas kick;

The compressibility of the mud is considered as a pressure build up:

$$p^{n+1} = p^n + \frac{\Delta V_{kick}}{(C_{mud} V_{mud} + C_{kick} V_{kick})} \dots\dots\dots\dots(8)$$

$$C_{kick} = \frac{1}{p} - \frac{1}{Z}\frac{dZ}{dP} \dots\dots\dots(9)$$

Step3: Circulation:

A constant BHP and an effective flow rate are taken as boundary conditions.

A flow pattern is supposed to vary with the fraction of bubbles gas:

Bubble flow if $Hg < 0.25$

Slug flow if $0.55 < Hg < 0.75$

Annular flow if $Hg > 0.9$

Numerical solution:

An implicit finite difference scheme is used to solve the previous equations in two phase regions, where the central mean in both time and back space are used in the discretization scheme as shown in the following figure:

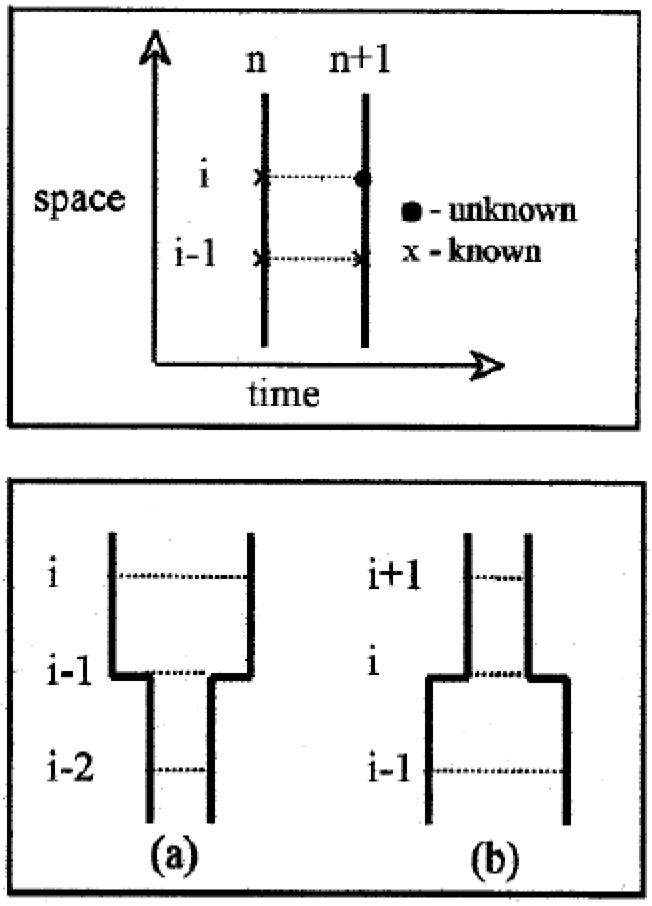


Figure 3-2: Discretization scheme.

These equations are designed to:

Geometry enlargement:

$$v_{mi}^{n+1} = v_{mi-1}^{n+1}\frac{(A\rho_m H_m)_{i-1}^{n+1}}{(A\rho_m H_m)_i^{n+1}} - \frac{\Delta x_i}{2\Delta t(\rho_m H_m)_i^{n+1}} - \left[(\rho_m H_m)_i^{n+1} + (\rho_m H_m)_{i-1}^{n+1} - (\rho_m H_m)_i^{n} - (\rho_m H_m)_{i-1}^{n}\right] \ldots\ldots\ldots\ldots(A1)$$

$$H_{gi}^{n+1} = \frac{(A\rho_g v_g H_g)_{i-1}^{n+1} - \frac{A_i \Delta x_i}{2\Delta t}\left[(\rho_g H_g)_{i-1}^{n+1} - (\rho_g H_g)_i^n - (\rho_g H_g)_{i-1}^n\right]}{(A_i \rho_{gi}^{n+1}(v_{gi}^{n+1}\frac{\Delta x_i}{2\Delta t})} \text{........}(A2)$$

$$p_i^{n+1} = p_{i-1}^{n+1} - \frac{\Delta x_i}{2\Delta t}(RV_i^{n+1} + RV_{i-1}^{n+1} - RV_i^n - RV_{i-1}^n) - \frac{1}{2A_i}(RV2_i^{n+1} + RV2_{i-1}^{n+1} - RV2_i^n - RV2_{i-1}^n)$$
$$-\frac{\Delta x_i}{4}(\frac{dp}{dL_i}^{n+1} + \frac{dp}{dL_{i-1}}^{n+1} + \frac{dp}{dL_i}^n + \frac{dp}{dL_{i-1}}^n) - \frac{980\Delta x_i}{4}(RV3_i^{n+1} + RV3_{i-1}^{n+1} + RV3_i^n + RV3_{i-1}^n) \text{.......}(A3)$$

where :

$$RV = \rho_m v_m H_m + \rho_g v_g H_g$$
$$RV2 = A\rho_m v_m^2 H_m + A\rho_g v_g^2 H_g$$
$$RV3 = \rho_m H_m + \rho_{gg} H_g$$

Reduced geometry:

$$v_{mi}^{n+1} = \left\{ v_{mi-1}^{n+1}\frac{(\rho_m H_m)_{i-1}^{n+1}}{(\rho_m H_m)_i^{n+1}} - \frac{\Delta x_i}{2\Delta t(\rho_m H_m)_i^{n+1}}\left[(\rho_m H_m)_i^{n+1} + (\rho_m H_m)_{i-1}^{n+1} - (\rho_m H_m)_i^n - (\rho_m H_m)_{i-1}^n\right] \right\}\frac{A_{i-1}}{A_i} \text{............}(A4)$$

$$H_{gi}^{n+1} = \frac{(\rho_g v_g H_g)_{i-1}^{n+1} - \frac{\Delta x_i}{2\Delta t}\left[(\rho_g H_g)_{i-1}^{n+1} - (\rho_g H_g)_i^n - (\rho_g H_g)_{i-1}^n\right]}{\rho_{gi}^{n+1}(v_{gi}^{n+1}\frac{A_i}{A_{i-1}} + \frac{\Delta x_i}{2\Delta t})} \text{........}(A5)$$

$$p_i^{n+1} = p_{i-1}^{n+1} - \frac{\Delta x_i}{2\Delta t}(RV_i^{n+1} + RV_{i-1}^{n+1} - RV_i^n - RV_{i-1}^n) - \frac{1}{2A_{i-1}}(RV2_i^{n+1} + RV2_{i-1}^{n+1} - RV2_i^n - RV2_{i-1}^n)$$
$$-\frac{\Delta x_i}{4}(\frac{dp}{dL_i}^{n+1} + \frac{dp}{dL_{i-1}}^{n+1} + \frac{dp}{dL_i}^n + \frac{dp}{dL_{i-1}}^n) - \frac{980\Delta x_i}{4}(RV3_i^{n+1} + RV3_{i-1}^{n+1} + RV3_i^n + RV3_{i-1}^n) \text{.......}(A6)$$

3.3.Rheology models:

Rheology is a Greek word that comes from the words reo, meaning to float, and logy meaning science. Rheology deals with the study of deformation and flow of matter (mainly liquids and in some cases solids and soft solids). In short, the drilling fluid flow property is characterized by their rheological properties, which are a function of composition of the drilling fluid, temperature and pressure. Drilling fluid helps to remove cuttings from the wellbore by keeping the cuttings in suspension during drilling. Other characteristics are minimizing friction during pumping, minimizing impact on the formation as we drill and being able to separate the cuttings at surface. It is important analyze fluid flow velocity profiles, fluid viscosity, frictional pressure losses, ECD, and annular hole cleaning. It is the basis for all analyses of wellbore hydraulics.[21] [30]

Flow properties for drilling mud is often characterized by the following rheology properties:

- Plastic viscosity (PV).
- Yield limit (YP).
- Gel strength.
- Apparent viscosity (AV) and Funnel viscosity ("Marsh Funnel").

The fluids can be divided into two groups according to their rheological properties; these are Newtonian fluids and non-Newtonian fluids, respectively.

3.3.1.Newtonian fluids:

Newtonian liquids have a viscosity, which is independent of shear rate. They are simple and clean liquids containing no particles larger than molecules. For instance liquids such as water, oil, and glycol behave as Newtonian fluids [30]. Given as Eq. 1 the shear stress is directly proportional to shear rate:

$$\tau = \mu \cdot \gamma \qquad \text{……………………………(1)}$$

Where:

τ: is shear stress.

μ: is viscosity and γ is shear rate.

3.3.2.Non-Newtonian fluids:

Unlike the Newtonian fluids, the viscosity for non-Newtonian fluids depends on shear rate. These are divided into three main categories: Plastic liquids, pseudo plastic fluids and dilatants fluids. It follows that the assortment of drilling fluids will be either plastic or pseudo plastic fluids.

In short, the main difference between plastic and pseudo plastic fluids are that plastic fluids have yield strength and a pseudo plastic does not.

Still, both are simultaneously shear thinning, i.e. AV decreases with increasing shear rate. Two examples of plastic and pseudo plastic fluids; water with added bentonite, and water containing polymers .The following rheology data set given in Table 1 is used as an example for how the different rheology parameters may be determined by using both graphics and equations. The fluid is made out of water, bentonite, polymer and barite.

The main goal will be to determine the rheological model that is best fitted to describe the given Fann data in Table 1.

Table 1 : Fann data

RPM	Reading [°]
600	54.50
300	43.50
200	37.50
100	32.00
6	23.00
3	20.50

3.3.2.1.Bingham Plastic model:

The Bingham model best describes liquids that have a yield point, and includes suspension of solids. The model is widely used to describe the condition of drilling fluid. Nevertheless, it is not suitable for viscosity and pressure loss calculations. The model is based upon two measurements that are performed by a Fann viscometer, respectively at 600 and 300 rpm. It is from these measurements possible to calculate the different rheological properties. However, it does not represent the most accurate behavior of drilling fluid at the bit (very high shear rate) and in the annulus (very low shear rates).

To describe a fluid in the best possible way, good mathematical models needs to be developed; perhaps one of the most famous of these is the Bingham-plastic model. It follows from Figure 2 that the equation for shear stress (τ) is given by Eq. 2 [30]:

$$\tau = \tau_p + \mu_y \cdot \gamma \qquad \text{……………………………….(2)}$$

Where the yield point, τ_p (YP) and plastic viscosity, μ_y (PV) can either be read from a graph similar to Figure 2 or calculated by using Eq. 3 and Eq. 4.

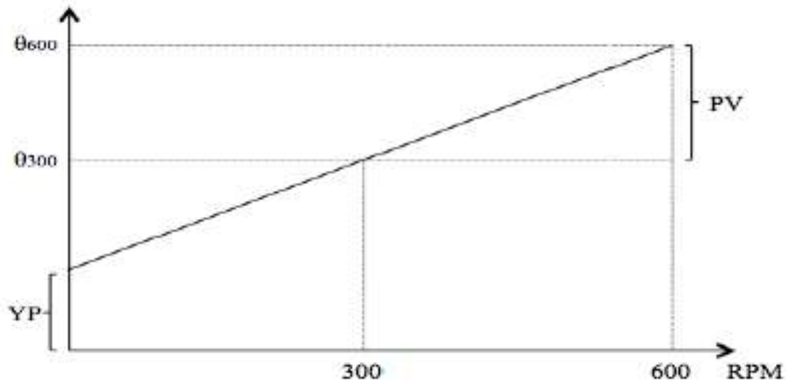


Figure3-3: Bangham plastic model

The slope of the curve in Figure 2 represents the plastic viscosity (μ_p).

$\mu_p\ cP = \theta_{600} - \theta_{300}$ ……………………………(3)

Curve intersection with the shear stress y-axis gives the yield strength in Eq. 5.

$\tau_y\ lbs/100ft^2 = \theta_{600} - \mu_p = 2 \cdot \theta_{300} - \theta_{600}$ ……………………………(4)

Using Eq. 3 and Eq. 4 and values from Table 1 the parameters μ_p (PV) and τ_y (YP) can be determined.

$\mu_p = 54.50 - 43.50 = 11\ cP$

$\tau_y = 43.50 - \mu_p = 32.50\ lbf/100\ ft^2$

3.3.2.2.Herschel Bulkley model:

The Herschel-Bulkley model is a modified version of the power-law model and is the modelthat normally describes the measured data best. By defining a third parameter, yield stress (τ_0), it is possible to get better results at low shear rates. The model is defined by Eq. 5 [11] [30]:

$\tau = \tau_0 + K(\gamma)^n$ ……………………………(5)

or

$\log(\tau - \tau_0) = \log(K) + n\ log(\gamma)$ ……………………………(6)

In comparison to Bingham, the model is using three parameters to describe the rheological behavior; therefore an initial calculation of τ_0 is required for calculation of the other parameters Eq. 7.

$$\tau_0 = \frac{\tau^{*2} - \tau_{min} \cdot \tau_{max}}{2 \cdot \tau^* - \tau_{min} - \tau_{max}} \quad \text{....................................(7)}$$

where τ^* is the shear stress value, corresponding to the geometric mean of the shear rate, γ^* and is calculated by interpolation.

$$\gamma^* = \sqrt{\gamma_{min} \cdot \gamma_{max}} \quad \text{...................................(8)}$$

Using Eq. 7 and Eq. 8 and values from Table 1. The parameters τ^*, γ^* and τ_0 may be determined.

$\gamma^* = 72.25\ sec^{-1}$
$\tau^* = 28.26\ lbf/100\ ft^2$
$\tau_0 = 20.14\ lbf/100\ ft^2$

Figure 3.4 and Table 2 shows the final results. A trend line was obtained using regression techniques.

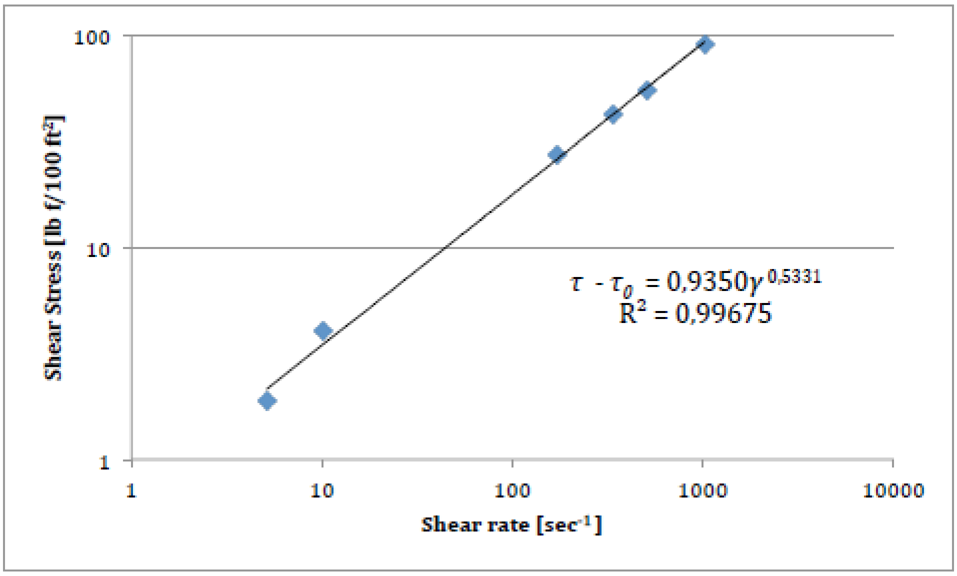


Figure 3.4 : Final results

From Figure 3, the Herschel-Bulkley parameters are as follows:
$n = 0.5331$
$K = 0.9350\ lbf/100\ ft^2$

Table 2 : Final results.

$\gamma\ [sec^{-1}]$	$\tau\ [lbf/100\ ft^2]$
1021,80	57,72
510,90	46,11
340,60	41,06
170,30	34,60
10,22	23,36
5,11	22,37

3.3.2.3.Robertson-Stiff model:

Robertson-Stiff model was developed as a more general model to describe the rheology behavior of drilling fluids and cement slurries. The model is given by Eq.9 [20]

$$\tau = A(\gamma + C)^B \qquad \text{...(9)}$$

or

$$\log(\tau) = \log(A) + B\log(\gamma + C) \qquad \text{...(10)}$$

Where:

A and *B* are model parameters similar to *n* and *K* in the Herschel-Bulkley model. Parameter *C* is the shear rate correction factor, so that the term $(\gamma + C)$ is considered the effective shear rate. Thus, τ is plotted against $(\gamma + C)$ on log-log coordinates, *B* is the slope and A is the intercept where $(\gamma + C) = 1$. Eq.11 represents the yield stress for the Robertson-Stiff model.

$$\tau_0 = AC^B \qquad \text{...(11)}$$

$$C = \frac{\gamma_{min} \cdot \gamma_{max} - \gamma^{*2}}{2 \cdot \gamma^* - \gamma_{min} - \gamma_{max}} \qquad \text{...(12)}$$

Where:

γ^* is the shear rate value corresponding to the geometric mean of the shear stress, τ^*, and is calculated by interpolation.

$$\tau^* = \sqrt{\tau_{min} \cdot \tau_{max}} \qquad \text{...(13)}$$

Again by using the data from Table 1, Eq.12 and Eq.13, the parameters τ^*, γ^* and C may be determined by calculations and interpolation.

$\tau^* = 35.66\ lbf/100\ ft^2$
$\gamma^* = 195.65\ sec^{-B}$
$C = 52.01\ sec^{-B}$

Figure 4 and Table 3 shows the results. A trend line was obtained by using regression techniques.

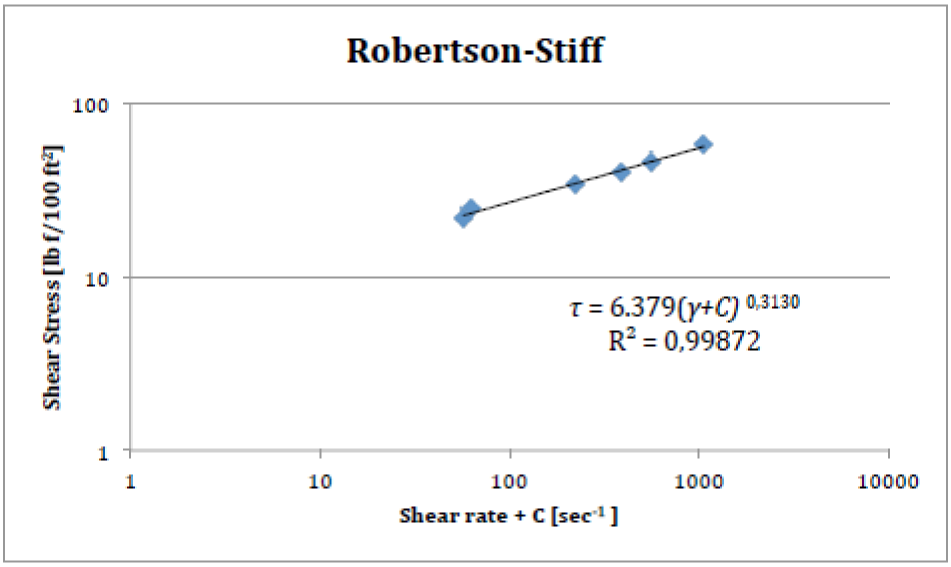


Figure 3-4 : Robenson- Stiff rheogram.

From Figure 4 the Robertson- Stiff parameters are as follows:
A = 6.379 $lbf.\ sec^B/100\ ft^2$
B = 0.3130

Table: Shear stress.

$\gamma\ [sec^{-1}]$	$\tau\ [lbf/100\ ft^2\ ]$
1021,80	56,70
510,90	46,32
340,60	41,38
170,30	34,63
10,22	23,25
5,11	22,63

Chapter04: Gas solubility in Oil based Mud:

Introduction:

In order to perform safe and efficient well operations, it is vital to comprehend how the gas influx behaves in drilling fluids. The oil based mud (OBM) may be contaminated by the gas during the drilling operation, and this can lead to a potential danger to the drilling equipment, environment and the personnel.

The biggest threat is when the gas completely dissolves into the drilling fluid, which is the case for some wells, and rapidly goes out of solution when the drilling fluid is circulated up in the well. [18]

4.1 Affecting solubility:

There are many factors that affect on solubility of gas in an oil-based mud. Some of these elements are presented as per below:

4.1.1 Pressure and temperature:

O'Bryan et al. have conducted some experiments related to the gas solubility, and how it is affected by the pressure and temperature. Their result proved that gas solubility increased with higher pressure, and decreased at higher temperature [18]

From the other side Thomas et al. demonstrated that the solubility actually increases with increasing temperature, at high pressures, which is contradictional to O'Bryan's observations. [33] This inconsistency of results is due to the solubility characteristics in a low volatility component of a critical solvent. This means that for high pressures the solubility increases with temperature, and at low pressures solubility in fact decreases with temperature. [2]

4.1.2 Composition of gas influx and base oil :

The major part of reservoir fluids is mainly composed of Methane, therefore it was used in most of the experiments performed about gas solubility and it's scope. [3]

The specific gravity of the gas has an effect on the solubility of formation gas in oil based mud; the higher specific gravity, the greater gas solubility. This is the case for low to intermediate pressures [18]. This also applies when methane is mixed with other compounds like toluene, which represents the aromatic particles of oil. The specific gravity will go up, and with smaller fractions of methane, the gas solubility increases [3].

When it comes to the composition of the based oil, it has negligible effects on the solubility at low pressures. However, at HPHT conditions, the gas solubility in base-oil differs when using different base-oil composition. For instance, the change of oil water ratio (OWR) in the mud will affect the solubility; the higher the OWR, the higher the gas solubility [18]

The chemical structure similarity of the base-oil and the methane has to be taken into account, as simpler base-oil composition can absorb more methane gas than complex structured base-oils [8].

4.1.3 Circulation:

Slow circulation rates, with resulting laminar flow in the annulus, may cause the gas to be “strung out” up the annulus. This means the gas-oil ratio (GOR) profile of the annulus will be stretched thin and cover a longer part of the annulus. Over time the gas-in-oil solution could cover the entire wellbore [10]

When the pump rate is at normal drilling rate, the flow regime around the drill collar section will be turbulent. This significantly increases the rate of gas dissolution, due to the mixing of the flow [22]

While having drilling fluid containing invading gas, the gas bubbles will be dispersed due to convection and molecular diffusion. The main mechanism, however, is believed to be convection as long as the well is being circulated. This convective process increases the solubility of the gas into the oil-based mud [19]

4.2 Consequences of gas dissolution:

The effect of gas solubility changes the properties of the drilling fluid when the gas is mixed into the mud, which can lead to well control issues. The fact that the formation volume factor of gas, relative volume of gas at reservoir conditions to the volume of gas at standard conditions, is different when gas is dissolved into mud could be a sign of that small changes of composition of the gas and liquid are taking place [24]

4.2.1 Rheological properties:

It is important to understand the alteration to the rheological properties of the OBM when gas mixes with the mud, due to the well control issues that can arise. When gas is dissolved into the OBM, the shear stress is heavily reduced, and similarly the viscosity is reduced. Results presented by Torsvik et al shows that OBM, based on linear paraffin, mixed with methane gives an effect of reducing the shear stress by about 40% [32]

4.2.2 Saturation pressure

With dissolved gas mixed into the OBM, the well run the risk of having gas boiling rapidly out of solution followed by a large volume expansion. This occurs when the wellbore pressure at a point is below the saturation pressure of the mixture. The consequences of flashed gas can be severe and may lead to a blowout at the surface or unloading of the riser [22].

The bottomhole pressure will be reduced and secondary kicks can be taken. The saturation pressure, the pressure where vapor and liquid are in equilibrium, initially increases rapidly with increasing GOR, but levels off with further increase in GOR. Therefore, for high concentration of dissolved gas, the gas will boil out of the mud-gas mixture deeper down in the wellbore than for low concentration of gas. However, the saturation pressure decreases for very high concentration of dissolved gas [8].

In terms of the OBM density, the saturation pressure remains the same with increasing GOR, so the GOR will still give the same effect independent of the density [24].

4.2.3 Density variation:

While drilling HPHT wells with invading gas it is important to correctly calculate the gas-mud mixture density. These kinds of wells are usually long, and minor inaccuracies in densities can have a considerable impact on the volume balance calculations throughout the well [32].

The density of oil-based drilling fluid is dependent of the pressure and temperature in the well [15].

The gas solubility, as mentioned earlier, also relies on the pressure and temperature. Gas mixed into the mud also has an effect on the density. O'Bryan et al presents results showing that when gas dissolves into the OBM, the density of the mud decreases [19].

4.3 Pressure-volume-temperature models:

Pressure-volume-temperature (PVT) properties such as saturation pressure, GOR, formation volume factors, mixed density, are necessary to predict the characteristics and behavior of drilling fluids at HPHT conditions. Therefore, one can either use an equation of state or PVT correlations to complete the missing data related to the properties of the mixed fluid.

4.3.1 Equations of state method:

With the intention of understanding the process of dissolution of gases in drilling mud, especially while operating in the borehole with higher pressures and temperatures, mathematical models using the equations of state have been developed. These models are used to simulate the mixture behavior under given conditions of gas concentration and pressure, where the pressure-volume-temperature equipment is limited and cannot give viable experimental data [1]. However, modeling with high pressures and temperatures may prove difficult for the simulators that extrapolate the results of experimental data, when approaching the critical region of the mixture.

Marteau et al. examined these risks and compared the different equations of state with experimental data and questioned if these models could be relied upon [14] For instance, Torsvik et al. showed that for density prediction of OBM, the two standard models, based on Peng Robinson and Soave-Redlich-Kwong equations of state. deviates from the experimental results regarding density differences under HPHT conditions. However, their work shows that by tuning the PVT models with a series of density measurements, the EOS's shows promising potential [32].

One example of a PVT simulator is PVTsim which is developed by Calsep3. This simulator uses equation of state to calculate phase behavior of petroleum fluids.

4.3.2 Pressure-volume-temperature correlations:

One of the earlier PVT correlations that model the dissolution of gas into oil was developed by Standing. However, Standing's work, which his PVT correlation is based on, is developed for California oils and does not make corrections for other oil types or non-hydrocarbon content. The correlation assumes that the saturation pressure is a function of dissolved GOR, density of fluids, and temperature [29]. It is common that PVT correlations are only developed for fluid properties in a certain geographical area. It is known that one correlation predicts one or more properties, like density or viscosity, better than other correlations. Therefore, a different correlation has to be used for different properties to achieve better results [34].

Chapter5: Simulation of the kick, Results and Discussion

Introduction:

This chapter is divided in two parts; the first part is devoted to the presentation of the tools and well data used for simulation of the kick and the configuration of the different parts of the simulation and the second part is about the discussion of the simulation results.

I .First Part: Simulation configuration of the kick

5.1. Simulator description:

Drillbench© is a drilling software package developed by Scandpower, with different modules for different purposes. The Hydraulics© module was used to compute the expected ECD and fluid density sensitivity analysis. The Pressmod© module was used to give a dynamic temperature model of the drillstring and annulus. It also helped in validating that the input parameters chosen could be used to drill the respective sections. The Kick© module was used to simulate several kick situations for conventional drilling, and the subsequent circulation of the influx. The kick module is a two phase flow simulator which can simulate kick situations, starting with influx and ending with circulation of the influx. Since it is fully time transient, the entire process can be visualized, and interactive actions can be taken at any time. This facilitates simulation of specific procedures like extended shut-in, altering the mud weight and so on. The graphical user interface of the software is easy and intuitive, as illustrated by Figure 1, which shows a simulation in Kick©. It does, however, ignore the effect of cuttings.

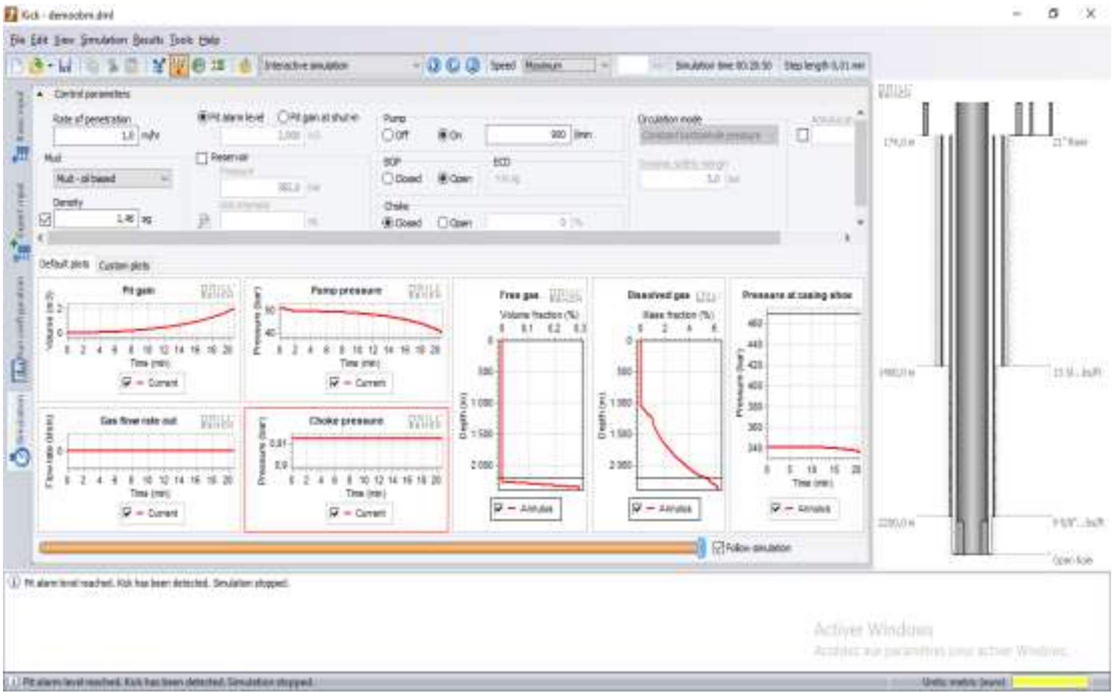


Figure 5-1: Drillbench© Software interface.

5.2. Base case description :

The Nezla field has had several kicks and eruptions since its development. In September 2006, the Nezla-19 well had a kick that erupted after several attempts of control. The consequences of this accident were disastrous, with 4 fatalities, 5 serious injuries and the loss of the drill rig that was ejected around the wellhead.

In this chapter the choice of the case study is focused on the NZ19 well located 120 km southeast of the Hassi Messaoud field and 100 km north of the Rhourde Nouss field, in the Berkine basin. The well was drilled to a depth of 2600 m in the Ordovician before that the eruption took place. After this tragic accident the well was abandoned.

The configuration as well as the NZ19 well data are presented in the following section:

5.2.1. Configuration of NZ19 well:

At the time of the kick, the drill bit was at the bottom of the well to a total depth of 2600 m in phase 5 7/8 in. The shoe of the liner 7 in is at a coast of 2153 m.

Well NZ19 is characterized by several productive areas. The objective of this drilling is to produce the following formations: the TAGI having for top 2234 m, the sandstone of Ouargla having for top 2265 m and the quartzites of Hamra having for top 2290 m.

It is assumed that the kick is taken in the Quartzite layer of Hamra, which is a porous and permeable formation. This formation contains fluids under abnormally high pressure evaluated at 382 bars.

The static temperature at the bottom of the well varies between 85 and 100 ° C. This gives a temperature gradient of 2.86 ° C / 100 m.

The configuration and lithology of the NZ19 well are presented in Appendix 01.

Drilling String:

The drilling string configuration is presented in the table 5-1below:

Drilling string of NZ19 well
141 m of 4 ¾ " DC (NC35-38), ID=2 in
192 m of 3 ½ HWDP (NC 38), ID=2.0625 in
To surface 3 ½ DP (G105, 13.5 lb/ft), ID=2.764 in

Drilling fluid:

The mud used for the drilling of phase 7/8 is a water-based mud whose rheological properties are presented in Table 5-2 below:

Mud parameters
Type: Oil based mud
Density: 1.34
Rheological model: Bingham
Plastic viscosity (PV)= 22cp
Yield point (YP)= 15 lb/100ft2

5.2.2. The characteristic of kick at NZ19 well:

- The 5 7/8 in phase is drilled in the Hamra Quartziltes containing gas at a pressure of 382 bars. The well is closed after detection of 2 m3 of gain in the maneuvering tank.
- The parameters recorded after well closure are used to evaluate the effect of the various parameters affecting annular pressure and shoe pressure with the two circulation methods, driller and W & W.

Table 5-3 shows the well parameters immediately after the well shutting.

Kick data	Pump characteristics
• **Kick size: 2m^3**	• Pump output: 13.74 l/Strokes
• **SIDPP: 40 bar**	• Flow rate: 25 SPM
• **SICP: 51 bar**	
• **Fracture gradient: 2.2 sg**	

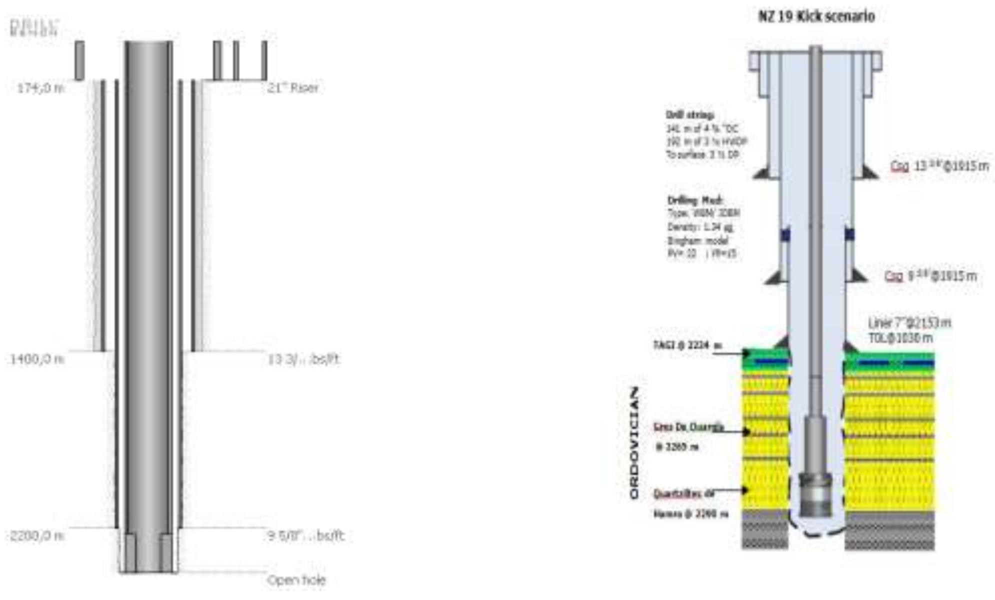


Figure 5-2: Well geometry

5.3. Parametric study of kick using Drillbench© Software:

This part of the simulations is carried out with the hydraulic model program Drillbench©. The NZ19 well data were used to carry out these simulations. This part of the simulations is interested in the study of the effect of different parameters and circulation methods on the variation of the solubility of gas in drilling fluid, of the annular pressure and the casing shoe pressure.

5.3.1. Effect of the type of drilling fluids:

Two simulations performed using two type of drilling fluids OBM and WBM to understand the gas kick behavior in the wellbore

The rheological parameters used are shown in figures below:

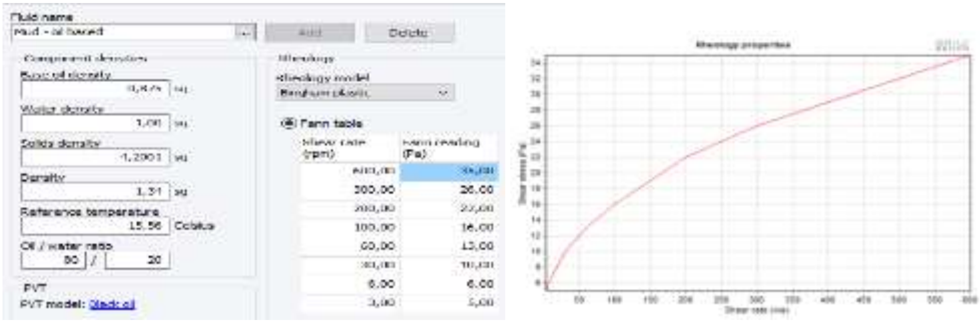


Figure 5-3 : OBM Rheology

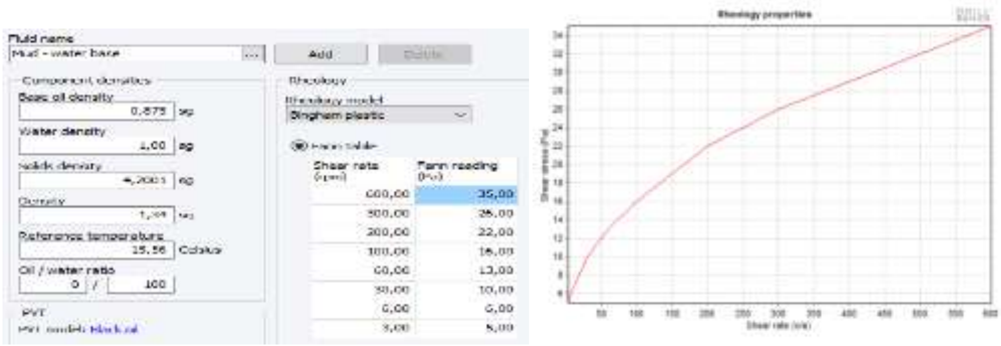


Figure 5-4 : WBM Rheology

5.3.2. Effect of the density:

Four simulations were performed using four values of the drilling fluid density to understand its influence on the wellbore pressure and solubility of gas kick, and also the scenario that happened in the well NZ19. The values of density are:

- 1.34 sg.
- 1.46 sg.
- 1.50 sg.
- 1.51 sg.

5.3.3. Effect of Kick Size:

Three simulations were performed using three values of the gain volume to see its influence on the solubility of gas in OBM, annular and casing shoe pressure. The volumes chosen are:

- 0,1 m^3.
- 01 m^3.
- 02 m^3.

5.3.4. Effect of Reservoir Pressure:

The effect of the reservoir pressure on the wellbore pressure and the solubility of gas in OBM is studied using three simulation. The pressure values chosen are:

- 382 bar.
- 360 bar.
- 340 bar.

5.3.5. Effect of Rate of penetration:

The effect of the rate of penetration on the wellbore pressure and the solubility of gas in drilling fluid is proved using three values .

- 1 m/hr.
- 2 m/hr.
- 4 m/hr.

5.3.6. Effect of Pump Rate:

The study of the pump rate's effect is done by three simulation with three values of pump rate.

- 900 l/m.
- 1200 l/m.
- 1500 l/m.

5.3.7. Effect of the Oil Water Ratio:

The ratio of oil to water percentage in the drilling fluid is defined as the Oil/Water Ratio (OWR). Four simulations are made to see how can the change of the OWR effect the solubility of gas. There are four oil water ratio values:

- 95/5
- 80/20
- 70/30
- 50/50

II. Second Part: Simulation results and discussion

5.1. Effect of the type of drilling fluid:

The below figures represent the kick simulation relating to the drilling mud type, where we observed that the gas behaves differently from OBM to WBM. The gas kick is completely dissolved in OBM but in WBM it keeps free gas in the wellbore.

If gas kick is taken in OBM and the well is closed , the gas kick will completely dissolve in the mud and stay at bottom until the well is circulated again. Also undetected kicks can be taken without a significant pit gain and they will not be detected before free gas starts to liberate of the solution when they are close to surface. For WBM the gas kick will be able to migrate up in the well even at closed in conditions.

With gas going into solution in OBM, pressure builds up until all the gas was dissolved and there was no further gas migration. However, gas kick migrates in WBM, and it builds up the pressure until gas reaches the surface.

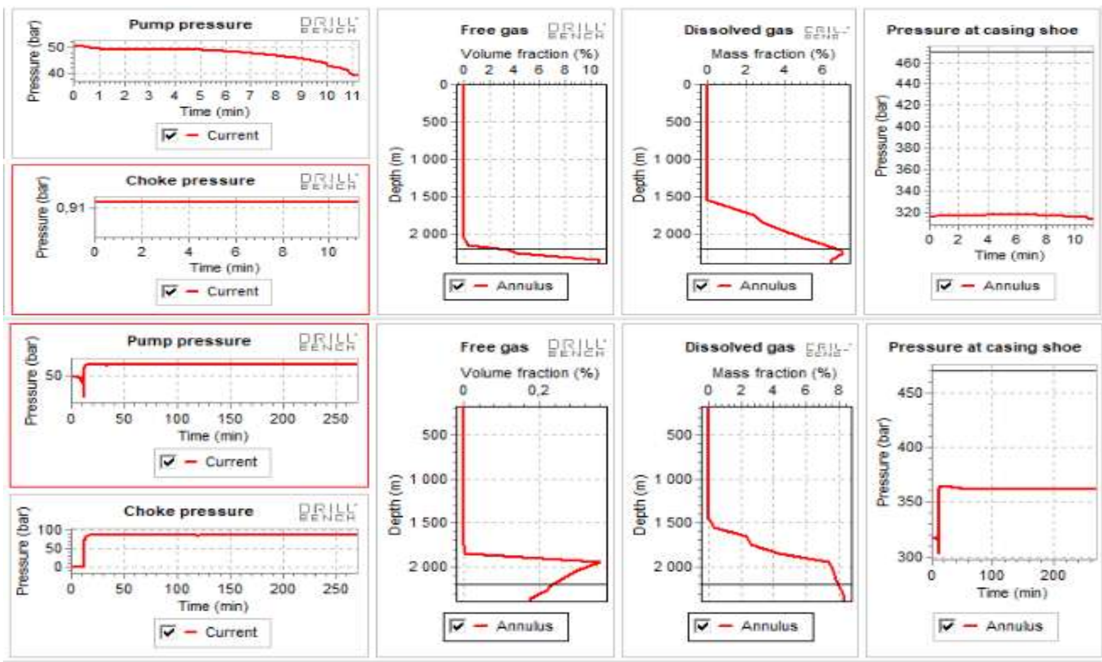


Figure 5-5 : OBM Simulation.

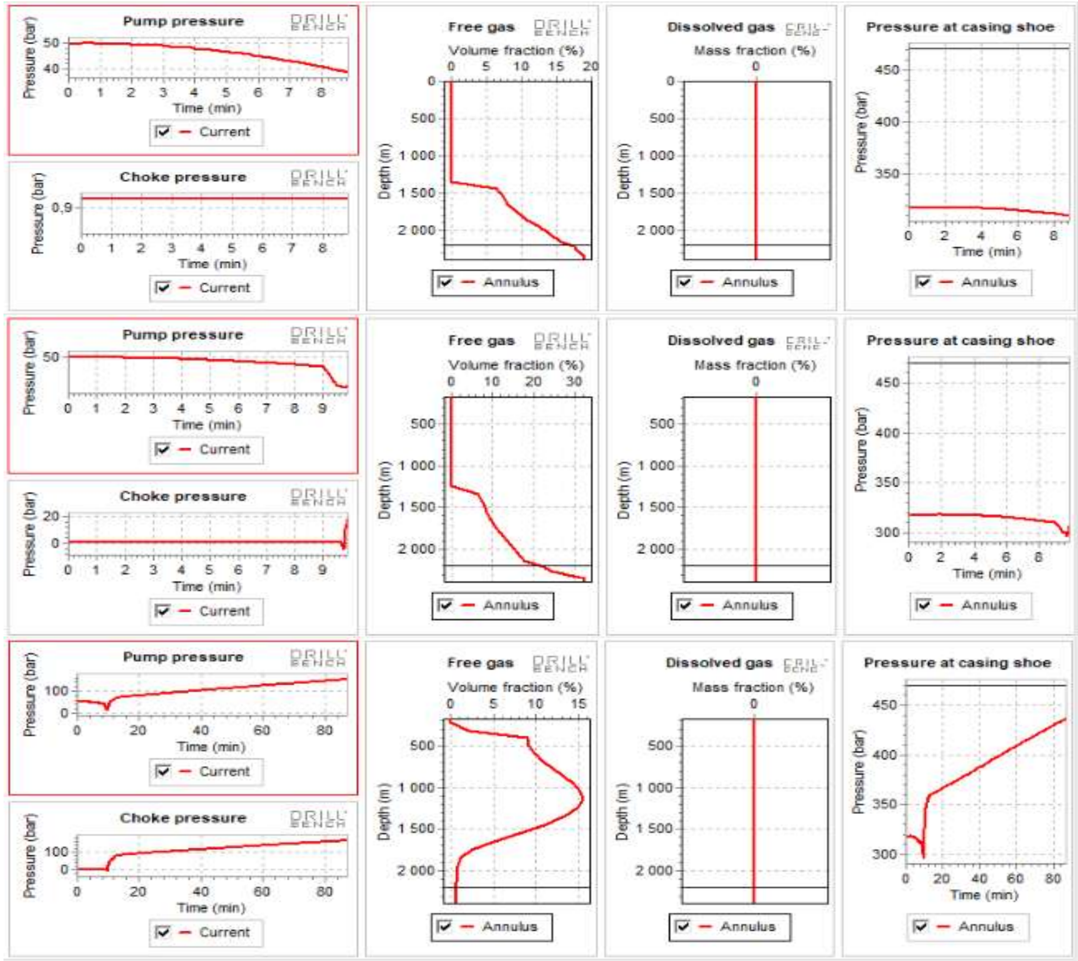


Figure 5-6 : WBM Simulation.

5.2. Effect of the density:

The results of the simulation of the effect of density are shown in the figure 5-7. The density value that was used in NZ19 is 1.34sg, while simulating with this value we observed that the kick was detected after 11 min. This value was not sufficient to maintain the wellbore stability.

In order to comprehend the density influence we worked with various values such as 1.46sg, 1.50sg and 1.51sg. The surface pit gain was maintained at the level of 2 ^{m3} for each case. We recognize that the solubility of gas decreases with the increase of the density and the kick height is vice versa.

For the NZ19 well, the density should be 1.51sg to overbalance the reservoir pressure. If the density of 1.50sg is chosen, they will drill on balance but some gas bubbles enter the well and decreases the hydrostatic pressure, in consequence the kick will occur.

The pressure in the casing shoe is increasing with the increase of density.

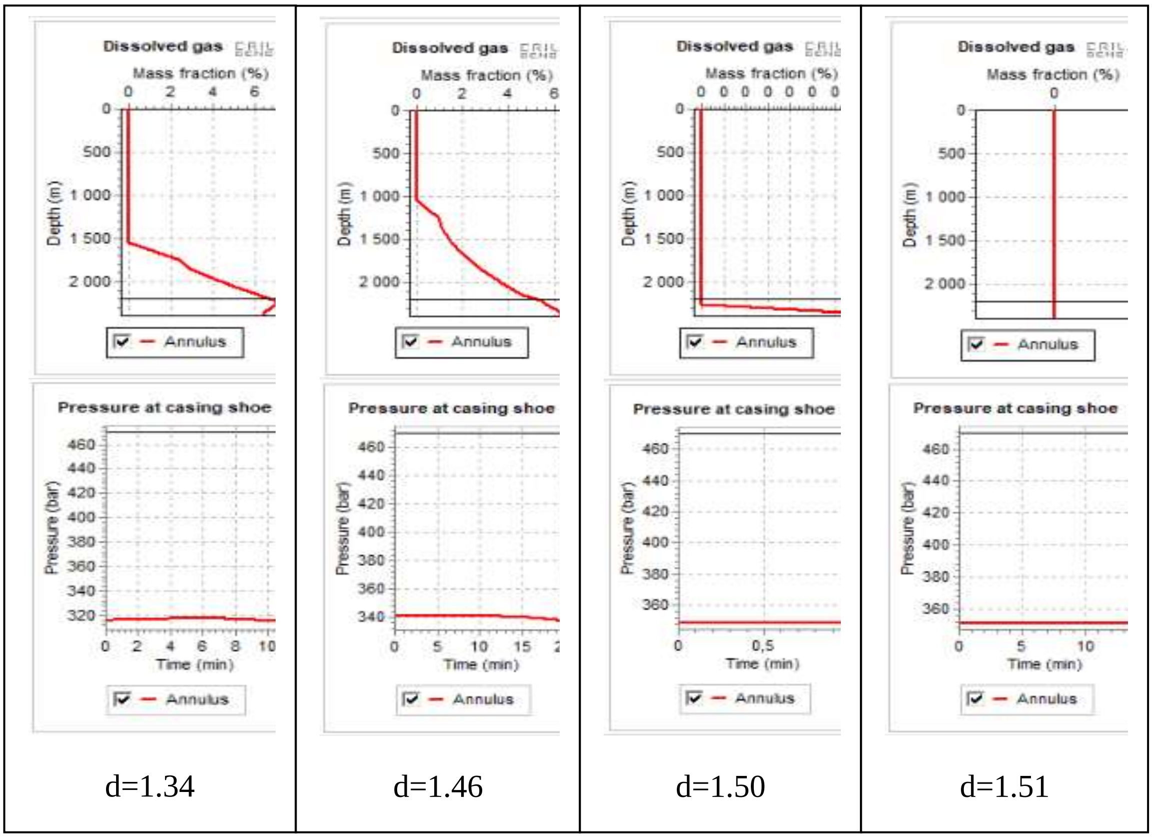


Figure 5-7: Simulation with different densities

5.3. Effect of Kick size:

The result of these simulations in figure 5-8 shows that the bottom hole pressure and the casing shoe pressure are very sensitive to the volume of gain and the gas solubility also it is influenced by the kick size.

The quantity of the dissolved gas and the height of the kick are increasing with the increase of the kick size. However the bottom hole pressure is decreasing from 353.5bar to 342.9bar and the casing shoe pressure is meanly changing from 319bar to 320bar.

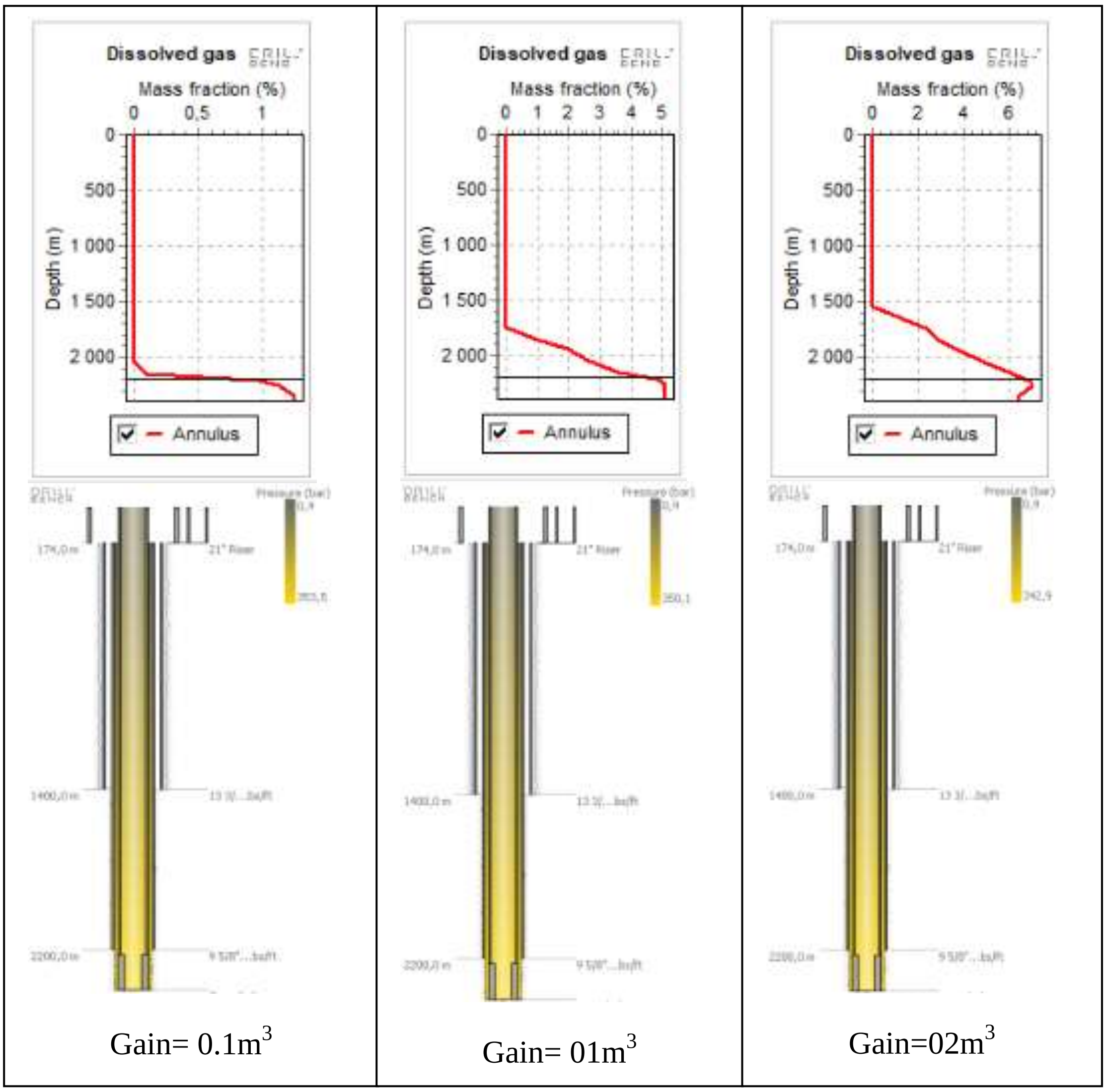


Figure 5-8: Simulation with different pit gain values.

5.4. Effect of Reservoir Pressure:

The influence of reservoir pressure on annular wellbore pressures and the solubility of gas in a vertical well drilled with OBM is illustrated in Figure 5-9. The change in reservoir pressure had a remarkable impact on the gas solubility and both surface and downhole pressures. The higher reservoir pressure resulted in a larger influx size into the wellbore. Even though the surface pit gain was maintained constant at $2m^3$, the total dissolved gas values increase with the increase of the reservoir pressure because of the kick intensity augmentation.

The hydrostatic pressure of the drilling fluid is decreasing because of the amount of dissolved gas that has a lower density then the drilling fluid.

This significant pressure increase may exceed casing burst pressure or fracture pressure at the shoe.

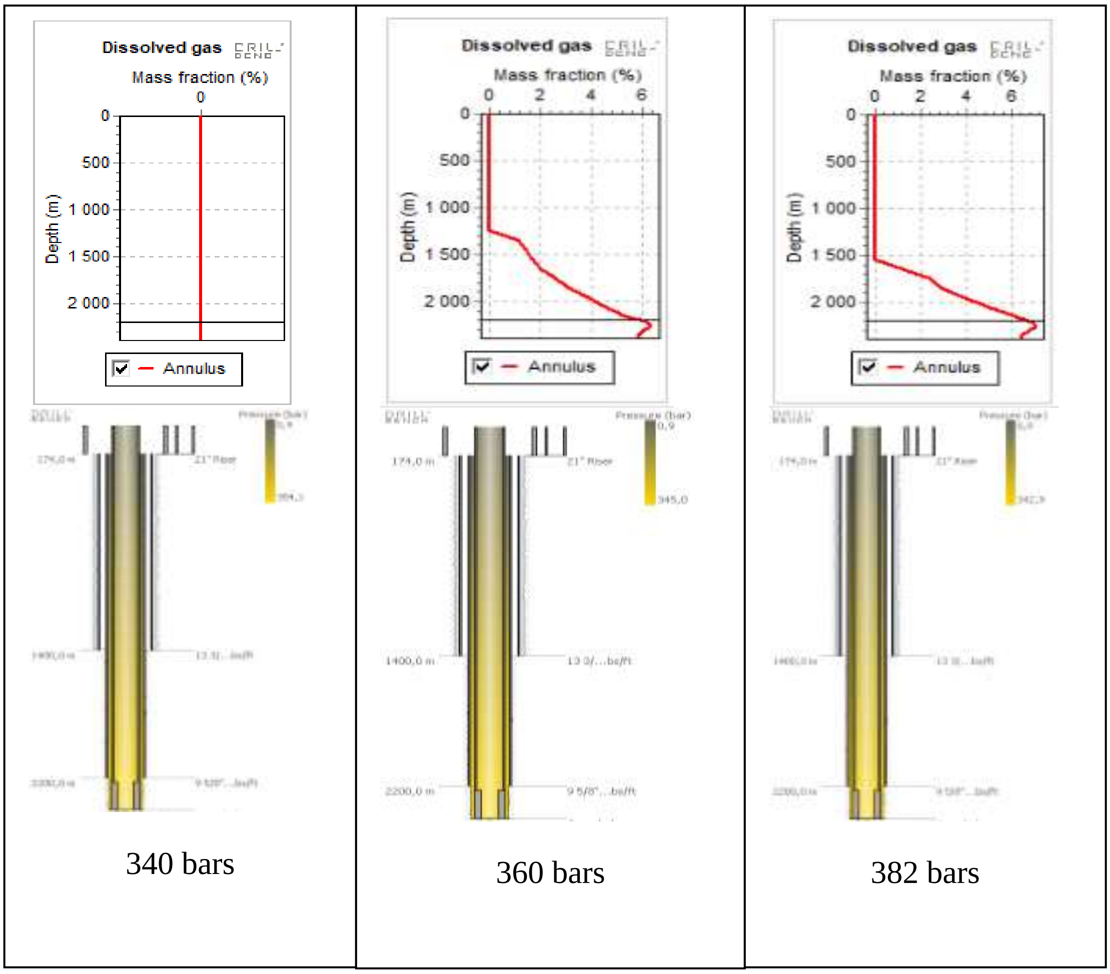
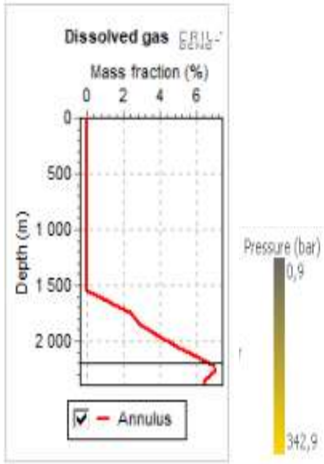


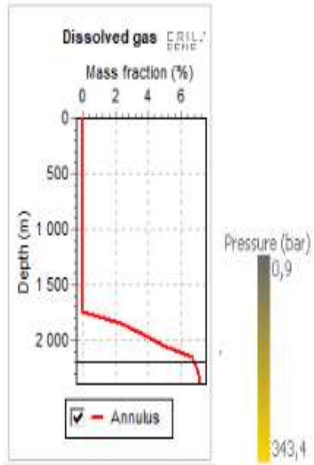
Figure 5-9: Simulation with different reservoir pressures

5.5. Effect of Rate of Penetration:

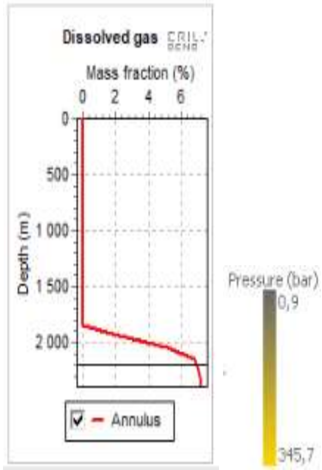
The influence of the ROP on annular wellbore pressures and the solubility of gas in a vertical well drilled with OBM is illustrated in Figure 5-10. The mass fraction of the dissolved gas in the drilling fluids is increasing meanly with the increase of the value of the ROP. However the height is decreasing remarkably because of the conditions in the downhole. The downhole pressure is increasing simultaneously with the increase of the ROP value.



ROP= 01m/hr



ROP= 02m/hr



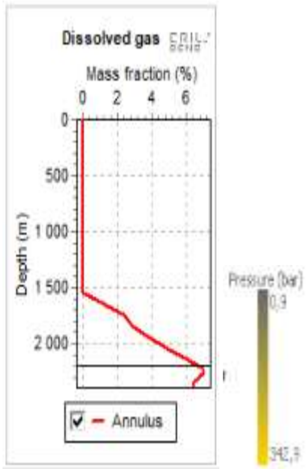
ROP= 04m/hr

Figure 5-10: Simulation with different ROP's

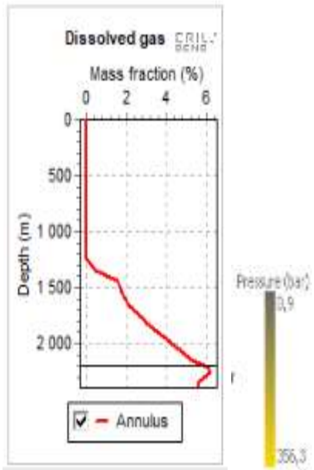
5.6. Effect of Pump Rate:

The below figure represents the simulation results with different pump rate values.

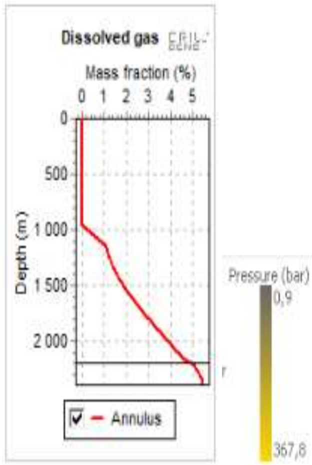
Pump rate is one of the main factors that effects the gas solubility same as the mud density, we observed that by the increase of the pump rate the gas mass fraction dissolved in the drilling fluid, and with this phenomenon the height gets higher as well as the wellbore pressure.



Q= 900l/m



Q= 1200l/m



Q= 1500l/m

Figure 5-11: Simulation of pump rate.

5.7. Effect of the Oil Water Ratio:

The below figure represents the OWR effect, Oil/Water ratio is the percentage of both fluids in a mixed mud, this value differs by the rheological composition of the drilling fluid, it has an important effect on gas solubility, in our study we observed that more the oil percentage is the dominating the water value the higher is the dissolved gas in the drilling mud, as consequence the wellbore pressure increases simultaneously.

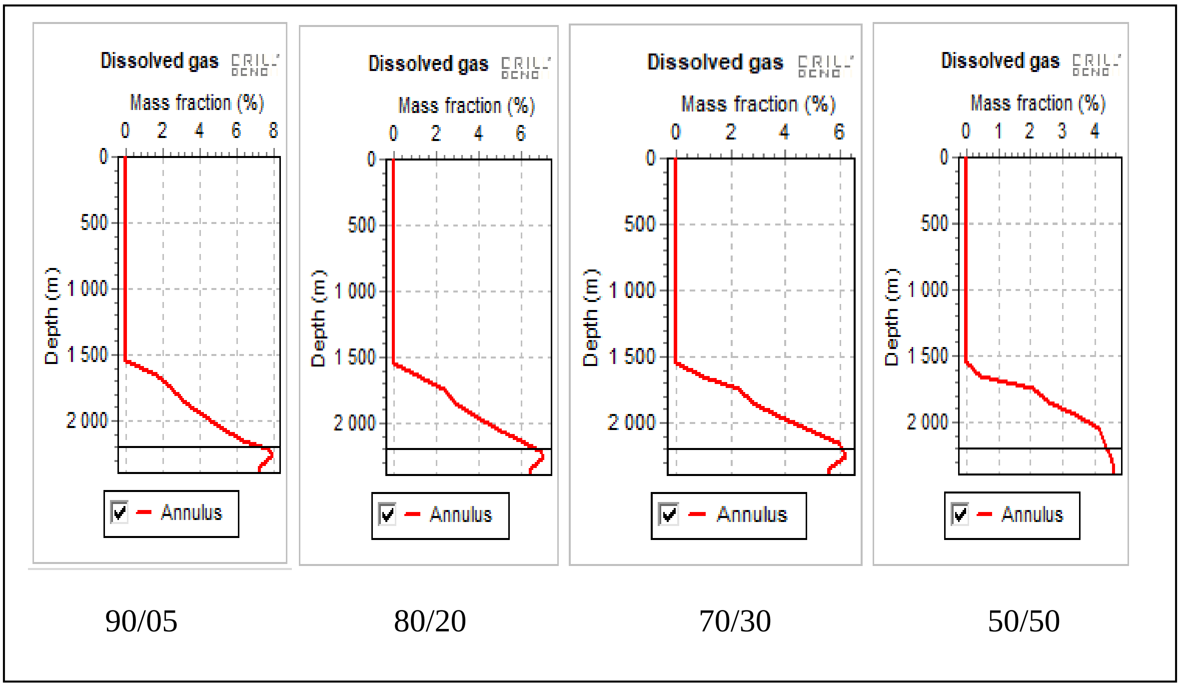


Figure 5-12: Simulation of OWR.

CHAPTER06: Conclusion, Recommendation and Perspectives:

From this study we can summarize the following conclusions, recommendations and perspectives:

6.1. Conclusions:

SONATRACH Kick's History:

The most common kicks were recorded during drilling with an insufficient density of drilling mud (an Underbalanced Kick).

The majority of the kicks are recorded in the field of Hassi Messaoud, which shows the complexity and heterogeneity of the HMD field.

Results of Simulations:

Among all the essays that were conducted, we have concluded that NZ19 kick could be avoided by the making the correct drilling parameters, density (d= 1.34) and wellbore pressure were not sufficient to control the well and keep the kick risk minimized, the correct density to work with in this case is (d=1.51) and above, therefore we agreed that density and since it is one of the parameters that we can control, is the most crucial factor that is involved directly with kick occurrence and also there are other factors that affect the gas solubility and wellbore pressure with different stages and degrees. As a matter of fact we must work with the accurate values of these factors to ensure the wellbore stability and avoid the kick occurrence.

The importance of the Kick Simulation:

Through this study it has been possible to demonstrate the usefulness of the kick simulation in the various stages related to the realization of a wellbore, however these tools of simulation can be used for:

- ✓ Risk Assessment

Simulations allow the determination of the most critical situation to prepare the most appropriate emergency safety plan.

- ✓ Well design
- Determine the kick tolerance for different types of fluids.
- Check the stability of the wellbore during the kick (fracturing the weak zone, evaluation of the losses during the circulation)
- Verify and validate the drilling program to ensure well integrity.
- Evaluation and improvement of the company's well control procedures.

- ✓ Drilling operations

Eruption simulation is an effective tool for decision-making on drilling sites and also allows updating of kick tolerance following unexpected changes or situations during drilling operations, for example:

- Change in the density of the drilling mud.

6.2. Recommendations

The training of the drilling site staff on the well control is strongly recommended because the success of the control of a possible kick depends essentially on the competence and the reactivity of the personnel.

Supervisors, superintendents and drilling engineers must be trained and informed about the preventative and curative measures of kicks in each field before start the drilling operation.

Underbalanced kicks can be avoided by a good estimate of reservoir pressure using DST data, wellbore stability analysis, and pore pressure from neighboring wells.

It is important to validate simulators and commercial software through comparative studies with existing models in the literature.

6.3. Perspectives:

The archiving of all kicks data is valuable in order to prevent accidents related to the same causes and circumstances from being repeated. These data are also fundamental to validate the correct simulation of the kick.

Bibliography:

- **[1] Atolini, T. M., & Ribeiro, P. R. (2007).** Vapor-Liquid Mixture Behavior at High Temperatures and Pressures: A Review Directed to Drilling Engineering. Brazilian Journal of Petroleum and Gas, 1(2), 123-130.
- **[2] Brunner, G. (1994):** Gas Extraction - An Introduction to Fundamentals of Supercritical Fluids and the Application to Separation Processes. New York: Springer.
- **[3] Bureau, N., de Hemptinne, J. C., Audibert, A., & Herzhaft, B. (2002):** Interactions Between Drilling Fluid and Reservoir Fluid. Paper presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas. SPE-77475-MS retrieved from http://dx.doi.org/10.2118/77475-MS
- **[4] CHOE, J., 2001.** Advanced Two Phase Well Control Analysis. JCPT .May 2001,volume 40, NO.5 .
- **[5] CHOE, J., and JUVKAM-WOLD, H. C., 1996**. Well Control Model Analyses Unsteady State, Two-Phase Flow. Oil & Gas Journal, December 1996, Pg. 68-77.
- **[6] CHOE, J., and JUVKAM-WOLD, H.C ,1997**. A modified two-phase well-control model and its applications as a training and educational tool. Society of Petroleum Engineers .SPE paper 37688.
- **[7] DRANCHUK, P.M. and ABOUKASSEM, J.H., 1975**. Calculation of Z Factors For Natural Gases Using Equations of State. Journal of Canadian Petroleum Technology, Vol. 14, No. 3
- **[8] Flatabø, G. Ø., Torsvik, A., Oltedal, V. M., Bjørkvik, B., Grimstad, A.-A., & Linga, H. (2015):** Experimental Gas Absorption in Petroleum Fluids at HPHT Conditions. Paper presented at the SPE Bergen One Day Seminar, Bergen, Norway. SPE-173865-MS retrieved from http://dx.doi.org/10.2118/173865-MS
- **[9] HASAN, A.R. and KABIR, C.S., 1986.** A Study of Multiphase Flow Behaviour in Vertical Oil Wells: Part I - Theoretical Treatment. SPE Paper 15138 presented at 56th California Regional Meeting of the SPE, Oakland, CA, 2 – 4April 1986.
- **[10] Hornung, M. R. (1990):** Kick Prevention, Detection, and Control: Planning and Training Guidelines for Drilling Deep High-Pressure Gas Wells. Paper presented at the SPE/IADC Drilling Conference, Houston, Texas. SPE-19990-MS retrieved from http://dx.doi.org/10.2118/19990-MS

- **[11] Kok, M.V. and T. Alikaya**, *Effect of Polymers on the Rheological Properties of KCl/Polymer Type Drilling Fluids*, Energy Sources, 2005, 27(5): p. 405-415.
- **[12] LeBLANC, J. L. and LEWIS, R. L., 1967**. A mathematical model of a gas kick. *SPE* paper 1860 presented at the SPE 42Annual Tech Conference fall meeting held in Houston, USA, 1-4 October 1967.
- **[13] Marteau, P., Obriot, J., Barreau, A., & Behar, E. (1997).** Experimental Determination of the Phase Behavior of Binary Mixtures: Methane-Hexane and Methane-Benzene. Fluid Phase Equilibria,129(1-2), 285-305. doi:10.1016/S0378-3812(96)03125-1
- **[14] Marteau, P., Obriot, J., Barreau, A., & Behar, E. (1997).** Experimental Determination of the Phase Behavior of Binary Mixtures: Methane-Hexane and Methane Benzene. Fluid Phase Equilibria,129(1-2), 285-305. doi:10.1016/S0378-3812(96)03125-1
- **[15] McMordie, W. C., Jr., Bland, R. G., & Hauser, J. M. (1982).** Effect of Temperature and Pressure on the Density of Drilling Fluids. Paper presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana. SPE-11114-MS retrieved from http://dx.doi.org/10.2118/11114-MS.
- **[16] NICKENS, H.V., 1987**. A Dynamic Computer Model of a Kicking Well. SPE paper 14183 presented at the annual technical conference and exhibition held in Las Vegas, USA, 22-25 September 1985.
- **[17] NUNES, J.O.L., BANNWART, A.C. and RIBEIRO, P.R., 2002**. Mathematical Modeling of Gas Kicks In Deep Water Scenario. IADC/SPE paper 77253 presented at the IADC/SPE Asia Pacific Drilling Technology held in Jakarta, Indonesia, 09-11 September 2002.
- **[18] O'Bryan, P. L. (1985):** The Experimental and Theoretical Study of Methane Solubility in an Oil Base Drilling Fluid. (Master), Louisiana State University, Baton Rouge, LA.
- **[19] O'Bryan, P. L., & Bourgoyne, A. T. (1989):** Methods for Handling Drilled Gas in Oil-Based Drilling Fluids. SPE Drilling Engineering, 04(03). doi:10.2118/16159-PA
- **[20] Ochoa, M.V., 2006**, *Analysis of Drilling Fluid Rheology and Tool Joint Effect to Reduce Errors in Hydraulics Calculations*, [PhD Thesis], Texas A&M University, p.99.
- **[21] Okafor, M.N. and J.F. Evers, 1992**, *Experimental Comparison of Rheology Models for Drilling Fluids*, [Conference Paper] SPE-24086-MS, presented at Western Regional Meeting, Bakersfield, California, March 30-April 1, 1992.81

- **[22] Rommetveit, R., Fjelde, K. K., Aas, B., Day, N. F., Low, E., & Schwartz, D. H. (2003).** HPHT Well Control; An Integrated Approach. Paper presented at the Offshore Technology Conference, Houston, Texas. OTC-15322-MS retrieved from http://dx.doi.org/10.4043/15322-MS
- **[23] SCAGLIARINI, S., 2010.** Review of the current well control status Gassi Touil. Algeria: Schlumberger Algeria.
- **[24] Silva, C. T., Mariolani, J. R. L., Bonet, E. J., Lomba, R. F. T., Santos, O. L. A., & Ribeiro, P. R. (2004):** Gas Solubility in Synthetic Fluids: A Well Control Issue. Paper presented at the SPE Annual Technical Conference and Exhibition, Houston, Texas. SPE-91009-MS retrieved from http://dx.doi.org/10.2118/91009-MS.
- **[25] SHACKELFORD, D.W., 2007**. Final Report on Well Control and Securing Repsol NZ19, Algeria,SONATARCH and Boots & Coots. Internal document of Sonatrach.
- **[26] SKALLE, P. and PODIO, A.L., 1998**. Trends extracted from 800 Gulf Coast blowouts during 1960-1996. IADC/SPE paper 39354 presented at the 1998 IADC/SPE Drilling Conference held in Dallas, USA, 3-6 March 1998
- **[27] SONATRACH and BOOTS & COOTS**. Well control incident report, well control
- cell. Internal document of Sonatrach.
- **[28] SONATRACH, 2006. Nezla** 19 Blowout: mentoring well control. Internal document of Sonatrach.
- **[29] Standing, M. B. (1947).** A Pressure-Volume-Temperature Correlation For Mixtures Of California Oils And Gases. Paper presented at the Drilling and Production Practice, New York, New York.
- **[30] Strand, S., 1998,** *Øvinger i bore- og brønnvæsker*, Høgskolen i Stavanger, Stavanger.
- **[31] Trygve Birkeland**, Automated Well Control Using MPD Approach.2009**.** Erling Strand, Hydraulic Calculations Using Discovery Web for Visualization. 2009
- **[32] Torsvik, A., Skogestad, J. O., & Linga, H. (2016).** Impact on Oil-Based Drilling Fluid Properties from Gas Influx at HPHT Conditions. Paper presented at the IADC/SPE Drilling Conference and Exhibition, Fort Worth, Texas. IADC/SPE-178860-MS retrieved From http://dx.doi.org/10.2118/178860-MS.

- **[33] Thomas, D. C., Lea, J. F., Jr., & Turek, E. A. (1984):** Gas Solubility in Oil-Based Drilling Fluids: Effects on Kick Detection. Journal of Petroleum Technology, 36(06). doi:10.2118/11115-PA.
- **[34] Wu, R., & Rosenegger, L. (2000):** Comparison of PVT Properties From Equation of State Analysis and PVT Correlations for Reservoir Studies. Journal of Canadian Petroleum Technology, 39(07). doi:10.2118/00-07-03

Appendix01: NZ19 well Scheme