SPE/IADC 85310

Development and Testing of a Fully Automated System to Accurately Control Downhole Pressure During Drilling Operations.

E.J. van Riet, Shell International E&P Research; D. Reitsma, Shell International E&P Research; B. Vandecraen, IPCOS

Abstract

Accurate control over bottomhole pressure during drilling is essential as the industry meets increasingly challenging drilling environments such narrow drilling margin formations, HPHT wells and fractured formations.

To increase the accuracy of the control over bottom hole pressures during drilling, a fully automated prototype system consisting of a hydraulics simulator, a computer controlled choke manifold and a pump as part of the mud return system has been developed and tested.

Rather than mud density alone, the system uses a reduced density mud in combination with a variable back-pressure at the annulus exit to achieve the required downhole pressure. The system is able to substantially compensate downhole pressure variations induced by the drilling operation by varying the surface back-pressure.

A number of possible advantages are associated with the use of the system:

- Reduction of formation impairment
- Reduction of mud losses
- Reduction of formation fluid influx
- Increased ROP
- No flat time during weight-up/down
- Potential to reduce number of casing strings
- Automatic kick circulation

A successful experimental program has been conducted on a real size test well in preparation of a field test sequence.

The system was easily retrofitted to the existing test rig and normal drilling procedures were minimally impacted.

Introduction

Accurate control over bottomhole pressure during drilling is essential as the industry operates in increasingly challenging drilling environments, some of which are:

1) Narrow margin between pore and fracture pressure where static and dynamic equivalent circulating density or surge and swab effects can result in significant mud losses[1] or well control events.
2) HPHT wells where formation pore and fracture pressure determination by adjusting the mud weight in small increments is time consuming.
3) Fractured or highly permeable reservoirs where equivalent circulating density is above pore pressure and LCM is not effective resulting in early termination of the well due to losses or in the requirement to drill with a mud cap[2] or underbalanced.
4) Transients during underbalanced drilling (UBD) exceeding pore pressure resulting in lost benefits of UBD.
5) Mechanical hole stability where weighting-up can result in significant flat time.

These difficult drilling conditions are now managed by incorporating bottomhole pressure control procedures primarily using mud density control and to a lesser extent control over pump rate. Manual back-pressure control methods using surface pressure and chokes have also been used[3], however automation is essential in these more demanding environments to maintain a constant bottomhole pressure with a high degree of accuracy and dependability.

This paper will discuss the novel design and full scale testing of a fully automated system to maintain an essentially constant bottomhole pressure during drilling operations. The system consists of a computer controlled choke manifold and pump as part of the surface mud return system. The downhole pressure is then controlled by automatic adjustment of the choke manifold and pump based on various inputs and the calculation results of a hydraulics simulator. Possible operational methods and considerations are also discussed.

Theory

In conventional drilling, the downhole pressure ($P_{downhole}$) is composed of the following two main components:

1. The hydrostatic pressure of the mud column including cuttings (P_{stat}).
2. The hydrodynamic pressure in the annulus induced by various effects such as mud flow or drill pipe movement (P_{dyn}).

This can be expressed by the following equation:

$$P_{downhole} = P_{stat} + P_{dyn} \qquad \text{eq.1}$$

To obtain the correct downhole pressure during drilling, the hydrostatic pressure of the mud column is usually adjusted by changing the density of the mud. Hydrodynamic pressure variations will always result in downhole pressure variations during conventional drilling and are not easily controlled.

The concept of the system described in this paper is the addition of back-pressure (P_{back}) at the annulus exit at surface. This back-pressure creates an additional control over downhole pressure. The downhole pressure can then be expressed as:

$$P_{downhole} = P_{stat} + P_{dyn} + P_{back} \qquad \text{eq.2}$$

Equation 2 illustrates that downhole pressure variations caused by variations of P_{stat} or P_{dyn} can be compensated by variation of P_{back}.
The equations 1 and 2 are depicted schematically in figs.1a and 1b. Fig. 1a illustrates the static situation (P_{dyn} = 0). Fig.1b illustrates the situation where $P_{dyn} \neq 0$ and how P_{dyn} is compensated by reducing back-pressure.

Advantages

A number of advantages are associated with the ability to apply a back-pressure on the annulus exit. First of all, several advantages are associated with the ability to maintain a controlled downhole pressure extremely close to the pore pressure resulting in:

- Minimizing formation damage
- Prevention of mud losses
- Prevention of formation fluid influx
- Increased ROP

Secondly, the ability to adjust back-pressure enables further optimization of the drilling operation, possibly resulting in casing strings to be set deeper or eliminated as illustrated in fig. 1b.

Thirdly, the controlled back-pressure allows instanteneous control over downhole pressure, weighting-up or down of the mud and extensive periods of mud circulation can be reduced or eliminated. Furthermore, formation fluid or gas influx or losses can be stopped instantaneously without the need to interrupt drilling.

Concept Selection of Back-Pressure System

During the early stages of the concept development, it was concluded that the back-pressure system had to meet a number of technical objectives to be successful:

- Quick response time to compensate for P_{dyn} variations
- Sufficient pressure range
- Ability to provide back-pressure, irrespective of return flowrate from the annulus
- Ability to handle cuttings
- Reliable and durable
- Servicable while operating.

To meet these objectives, several back-pressure generation concepts have been considered: The following discuss the most relevant concepts that have been evaluated.

Jet Pump opposing annulus return flow

It was considered to place a jet pump in the return flow conduit from the annulus. Fluid would be jetted in the opposite direction of the flow from the annulus, creating a pressure differential by momentum exchange between the jet stream and the flow from the well. The main advantages of this concept are that it can be made reliable, cheap and rugged since there are no moving parts that can be damaged by drilled solids. Furthermore, it can be designed having a full bore opening, consequently minimising risk of plugging by debris or cuttings from the well. Nevertheless, the concept was rejected because of the poor energy efficiency of the jet pump which would be in the order of a few percent under realistic conditions, requiring impractical injection pump power.

Hydromotor driven by return flow with controlled brake on the drive shaft.

A hydromotor with a brake on the drive shaft was considered. All return fluid from the annulus would be guided through the hydromotor. A variable brake on the drive shaft would control the pressure drop over the hydromotor. The main advantages of this concept are the speed, accuracy and ease of the control. Nevertheless the concept was rejected because at present no hydromotors are available that can handle drilled solids.

Choke & Pump

The concept of a variable choke to generate back-pressure is proven in the field. For example, chokes are used for well control and UBD pressure control. A disadvantage of a choke is that it is impossible to control pressure when no flow is passing the choke. For this reason, a pump was included in the back-pressure generation system in order to provide sufficient flow through the choke at all times. This back-pressure generation concept was selected.

Back-Pressure System Design

After selection of the concept of a choke and pump as preferred back-pressure generation concept, all components of the system: choke manifold, computer control system and pump have been designed and built as an integral system.

Choke Manifold

A hydraulically operated choke manifold has been designed and built that incorporates the following functionality:

- Built-in redundancy to allow choke maintanance without the need to interrupt the operation. The manifold was therefore constructed with 2 identical legs. During normal operation, only 1 leg is used and the other can be serviced if necessary. A switchover from one to the other leg can be performed automatically.
- Valving designed such that automatic start-up and shut-down of the back-pressure pump can always be performed.
- Ability to provide a full bore flow path to circulate out large debris.
- Selectively include fixed or variable chokes.

Figs. 2a and 2b show the manifold installed on the test site.

Computer System

The computer sytem calculates the back-pressure required to maintain the desired downhole pressure, it controls the choke manifold and runs the user interface. The computer system consists of a network of:

- One PC running a hydraulics simulator. This computer calculates the back-pressure set-point in real time from operational input data obtained from the rig data system, system-own sensors and information about the well geometry that is provided by the user. If the system is used in combination with a PMWD sub, the hydraulics model is calibrated automatically in real time.
- One PC is used to run the graphical user interface of the system, provide the data link with the rig data system and provide communication with the PLC.
- A Programmable Logic Controller (PLC) is used to control the choke manifold and pump and to aquire system-own sensor data.

A simplified schematic overview of the computer system is given in fig. 3.

Pump

A positive displacement pump is required to generate sufficient flow through the manifold chokes when the flow returning from the well is insufficient to control the back-pressure. Additional flow is required for instance when the rig pumps are switched off. When required, the pump is automatically switched-on by the computer system.

The pump used during testing of the system was a conventional triplex plunger pump driven by a Diesel engine. The Diesel engine was instrumented to allow control via the PLC.

Additional Drilling Equipment Requirements

To operate the system, the following additional equipment was required:

- A Rotating Control Head. The RCH is used to contain the annulus pressure.
- A Drill-string non-Return Valve. The DRV is used to prevent mud back-flow through the drill pipe when the back-pressure system is active and the drill string is open ended at surface, for instance when making a connection.
- Piping to connect the various components.

A schematic diagram of a typical installation is depicted in fig. 4. The piping is installed in such a way that all conventional rig functionality is maintained.

Full Scale Testing

The complete back-pressure system was installed on the NAM SimWell test well in Schoonebeek, The Netherlands where it has been subjected to a comprehensive test program of approximately four weeks duration. The objectives of the test were to fine tune the system, evaluate the performance of the system under realistic drilling/tripping conditions and test operational procedures.

SimWell

The SimWell test facility is normally used for well control training purposes and to test rig equipment. It consists of a fully equipped rig and cased vertical hole approximately 1530m deep. Inside the 5 ½" casing, a 2 7/8" drill pipe is run to bottom. Nitrogen can be injected into the annulus at different depths along the well to simulate gas kicks. Rig sensors are installed and sensor data is logged with a rig data system. Downhole pressure is recorded in real time by a permanently installed pressure sensor.

Test program

A test program was conducted addressing the following topics:

- Performance benchmark of the system.
- Simulated drilling/tripping.
- Simulated drilling problems (hole bridging, choke plugging and fluid loss).
- Well control tests (undetected and detected gas kick).

A description of these tests and a selection of results are as follows.

Test results

Performance benchmark

To fine-tune, measure and evaluate the performance of the system, a number of step response tests were conducted while only one operational parameter was varied at a time. Some of these tests involved rig pump flowrate and string axial velocity variation. Some tests were repeated many times to arrive at the optimal system settings. Fig. 5 depicts an example result of a test during which rig pump flowrate was repeatedly changed between zero and 400 l/min, which was the maximum flowrate available. The figure shows three cycles of pump/on, constant rate, pump/off test. The difference between the cycles is the rate of change of the pump rate. The first cycle shows pump rate varying from zero to maximum in 2 minutes, followed by a +/- 10 minute period of constant pump rate and pumps off in 2 minutes. The second cycle was executed in a similar manner but the pump rate was varied in 1 minute. The pump rate during the third cycle was varied over thirty seconds. In the same graph has been depicted what would have been the variation of downhole ECD if the system would not have been installed.

The results show that the system is able to significantly reduce the downhole pressure variations. Furthermore, it can be observed that the rate of change of the rig pump flowrate influences the over/undershoot at the time of the transitions. Through continued tuning of the system it was possible to further reduce the negative and positive pressure variations. However, the faster the pumps are shut-off / turned-on, the larger the pressure variations occurring downhole.

Simulated drilling and tripping

In order to evaluate procedures and performance during drilling and tripping, a number of tests have been performed while drilling operations were simulated.

Tripping can be performed on SimWell exactly as carried-out on a working drilling rig. Since no real drilling can be done on SimWell, drilling was simulated by slowly moving the drill pipe into the hole with the rig pumps running. It has to be noted that no cuttings were present in the well during the tests.

Fig. 6 shows the results of a drilling and tripping test. During the first part of the test, a number of stands were pulled out of the hole. Hereafter, drilling two stands was simulated. The first stand was done at a relatively low ROP, the second stand at a relatively high ROP.

The results show that pressure variations caused by rig pump flow rate changes are significantly reduced by the system. However, at the time the rig pumps are rapidly shut down, a low-pressure spike occurs as explained previously. The rig pumps were shut down as quickly as possible, but had the driller been instructed to gradually reduce the pump rate, then the pressure spikes would have been significantly reduced as illustrated in Fig.5.

These tests also confirmed that the system did not interfere substantially with normal drilling operations and procedures.

Drilling problems

A critical aspect for successful application of the system is its behaviour should unexpected drilling problems occur. For this reason, a number of common drilling problems were simulated such as choke plugging, hole bridging and fluid loss.

Choke plugging

Choke plugging was simulated by partially closing a gate valve *behind* the manifold. The increasing pressure is similar to a choke plugging and is detected by the system. In order to compensate for the increased pressure, the choke opens automatically.

Hole Bridging

Hole bridging was simulated by partially closing a gate valve *in front of* the manifold. Comparible to a hole bridge, the flow resistance in front of the manifold increases and the system reduced back-pressure automatically in order to maintain a constant downhole pressure.

Fluid Loss

Fluid loss was simulated by diverting part of the return flow around the manifold. This caused a reduction of flow through the mainfold resulting in the choke adjusting automatically to maintain the set-point pressure.

Simulated drilling problem test results

The results of the simulated drilling problems tests have shown that the system is able to compensate for these problems and that the system behaved as anticipated. An example test result of simulated choke plugging is depicted in fig. 7.

The system could be further enhanced to provide the driller with an early warning of these potential problems based on response characteristics.

Well control tests

Another critical aspect of the system is its response during undetected or detected gas or fluid influx into the annulus. For this reason, automatic kick circulation using the 'Drillers' and 'Wait & Weight' methods was implemented in the computer system.

An undetected gas kick test and a detected gas kick test were conducted by injecting nitrogen downhole. The automatic execution of the 'Wait & Weight' and 'Drillers' methods were tested.

Undetected Gas Kick

An undetected gas kick was simulated by injecting a N2 gas bubble downhole and allowing this bubble to travel to surface while the back-pressure system was active. The results of this test have shown the downhole pressure variations were greatly reduced by the system, as compared with the kick not being detected during a conventional drilling operation. This is a result of the system automatically compensating for the reduced P_{stat} and adjusting to maintain the set-point downhole pressure.

The result of the test is depicted in fig. 8. This graph shows downhole pressure and back-pressure versus time. With the hydraulics model set to recalibrate every 10 minutes based on actual bottom hole pressure, the surface pressure was increased to compensate for the reduced P_{stat}. After a certain time, the gas reaches surface and exits via the choke manifold. While the gas exits the well, the system automatically decreases the back-pressure to the start condition.

Note that some oscilation can be observed while the gas flows through the manifold. This was caused by sub-optimal parameter settings during the test and has been resolved after the test was carried-out. Furthermore, some small pressure peaks are present at the start of the test. These peaks were caused by a manual step response test of the system.

Automatic kick circulation

During this test, a gas kick was injected downhole and the system switched to automatic kick circulation using the 'Drillers' method. According to this method the back-pressure was controlled to maintain a constant standpipe pressure while the kick was circulated out. Standpipe pressure readings were obtained by the back-pressure system from the rig data system and rig sensor.

The results of an automatic kick circulation test are shown in fig. 9. This graph shows downhole pressure and back-pressure versus time. The test was initialized by injecting a gas kick. Consequently, the downhole pressure decreases while the gas bubble increases in size. After sufficient gas was injected, gas injection was stopped and the downhole pressure was brought to the original value by increasing the back-pressure.

The automatic kick circulation was started. It can be observed that while the bubble travels to surface, the back-pressure is increased automatically in order to maintain a constant standpipe pressure (constant bottom hole pressure) as the gas bubble expands. After a certain time, the gas reaches surface and exits via the choke manifold. While the gas exits the well, the system automatically decreases the back-pressure as expected and returns to the start condition.

Wait & Weight method

The test involved automatically adjusting standpipe pressure to compensate for circulating the well to a higher density mud. In fig. 10 it can be seen that actual standpipe pressure precisely follows the automatically calculated standpipe pressure curve.

Operational Procedures & Considerations

Since the system runs automatically it is complimentary rather than invasive to the current drilling operation by providing an automated method to maintain bottomhole pressure, provide kick detection and control. A full-scale well test is planned that will help to fully determine other considerations which are discussed as follows.

Well Design

During the design phase of the well, the expected downhole pressure margin is determined. While this is not always completely accurate it is critical for determining casing shoe placement and maximum allowable casing pressure.

With the mud weight lower than conventional drilling and surface pressure used to offset the difference in ECD, the initial casing shoes may have to be set deeper to compensate for the lower mud weight since the hydrostatic pressure at the shoe will be slightly higher than usual.

In some cases most of the well may be drilled without surface pressure but with a reduced mud weight, only "weighting-up" by adding back-pressure when required for well control or hole stability. This could significantly reduce mud costs by reducing the requirement for weighting materials.

Rig Design

Since back-pressure is added to the entire well, including the standpipe/rig pump pressure, additional rig pump power and surface pressure ratings may be required to offset surface annular pressure.

Additional electric power will be required to operate the system. The main power requirement will be for the auxillary pump if electrically driven. Since this is a relatively small pump it would not require substantial power. Rig site size constraints should usually not be a problem since the components of the system have a small footprint.

The prototype version used hydraulically controlled chokes, so required a hydraulic power unit. In future, electrically driven chokes may be used and further reduce the footprint of the system.

BHA Design

It is desireable to include a real time PMWD sub to continuously recalibrate the flow model while drilling at least in the intial stages of drilling the well. Since the flow model is recalibrated as drilling continues, subsequent trips may not require the PMWD if only minor changes to the flow model are taking place. As a minimum it is thought that a bottomhole pressure recorder should be used so that the flow model can be calibrated after the first bit run.

To maintain well pressure on connections the use of drill string non-return valves are required to prevent backflow up the drill string.

Drilling shoe track / drilling hole

After the shoe has been cemented and the mud in the wellbore has been changed out to the correct mud, shoe track drilling / hole drilling proceeds as follows:

- The rotating control head is closed.
- The main pumps are engaged and back-pressure is automatically brought to the desired value by the back-pressure system.
- Drilling is commenced and returns monitored.

Connections

The back-pressure system automatically adjusts for the pumps being switched off. The drill string needs to be depressurized and a "Mud Can" used since the connection will be wet.

Tripping

Several options are available when tripping:

- Strip / Snub. The rotating control head is used to strip out of the hole until the string becomes pipe light but in some cases the surface pressure may be low enough that snubbing is not required. An advantage to this method is that surface pressure is maintained and allows the back-pressure system to continuously maintain well control.
- Circulate in a heavy mud pill to offset surface pressure. The advantage is that stripping and snubbing is not required however the fluid level in the well has to be maintained when tripping out. Displacement while tripping in also has to be considered since the heavy mud should not be displaced out of the well due to pipe displacement. The heavy mud pill however does have to be circulated out of the well to allow continued drilling with surface pressure at the previous bottomhole set-point pressure.
- Use of a downhole isolation valve installed with the casing or liner. Surface pressure is released after isolating the drill string above valve and allows for faster trips.
- Release surface pressure and trip out of the hole. This is not a likely scenario and would only be used if

there is no risk of a kick or loss of hole stability due to the reduced bottomhole pressure.

Conclusions

Accurate control over bottomhole pressure during drilling is essential as the industry meets increasingly challenging drilling environments such narrow drilling margin formations, HPHT wells and fractured/highly permeable formations.

To automatically and accurately control downhole pressure during drilling a novel system has been developed and has been subjected to a comprehensive test program on a real size test well. The results of the tests have proven the feasibility of the technique and there is sufficient confidence to proceed with actual well tests to test the system during an actual drilling operation.

The system applies a back-pressure to the annulus exit at surface using a computer controlled choke manifold and pump. The computer system receives input data from various sensors and utilizes this data to:

- Automatically calculate the required back-pressure to maintain constant downhole pressure on set-point. It performs these calculations continuously and in real time.
- Control the choke manifold and pump to generate the required back-pressure at all times.
- Provide automatic kick circulation.

The system can be retrofitted to existing rigs and would have minimal impact on conventional drilling procedures.

System enhancements could include early warning alarms for drilling problems.

Future developments

The prototype system was developed for proof-of-concept of the automatic downhole pressure control method set fourth in this paper. As next possible steps in the development of the automatic pressure control technique, control system enhancements would enable application in the following areas:

- Drilling with dual gradient / gassified drilling fluids.
- Underbalanced drilling.
- Automatic volumetric kick circulation methods and improved kick detection.
- Pressurized mud-cap drilling.

Acknowledgements

The authors thank the SimWell crew for their support during the execution of the experiments.

References

1. T. Meader,F. Allen, G. Riley: “To the Limit and Beyond – The Secret of World-Class Extended-Reach Drilling Performance at Wytch Farm”, IADC/SPE 59204, Feb 2000, IADC/SPE Drilling Conference New Orleans.

2. M. Anuar Taib: “Carbonate Drilling with Mud Loss Problems in Offshore Sarawak”, IADC/SPE 36394, Sept 1996 IADC/SPE Asia Pacific Drilling Technology, Kuala Lumpur, Malaysia.

3. D.D. Kara, D.T. Hearn, L.L.Gantt, C.G. Blount: “Dynamically Overbalanced Coiled Tubing Drilling on the North Slope of Alaska”, SPE 72058, SPE Drilling & Completion, June 2001.

Nomenclature

All units metric

P_{back}	=Back-pressure	[bar]
$P_{downhole}$	=Downhole Pressure	[bar]
P_{dyn}	=Hydrodynamic Pressure	[bar]
P_{stat}	=Hydrostatic Pressure	[bar]

SI Metric to English conversion factors

[bar]	x 14.504	= psi
[l/min]	x 0.2642	= GPM

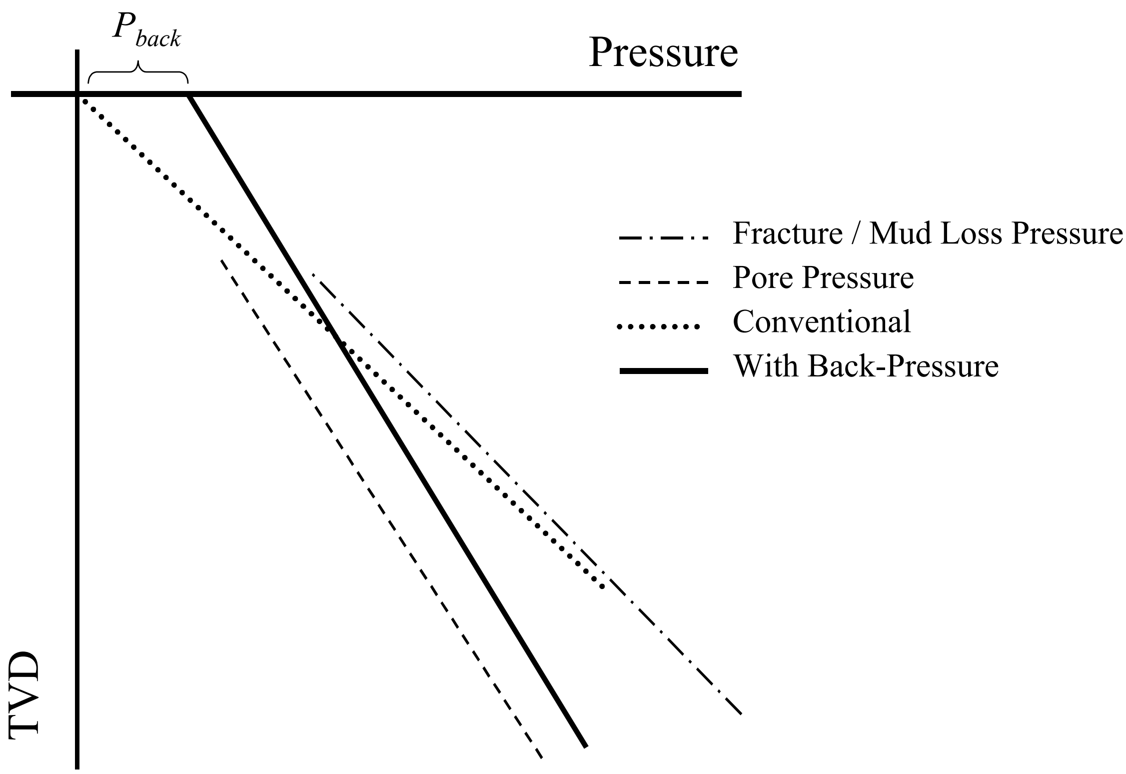

Fig. 1a. Schematic comparison static pressure distribution during conventional drilling and during drilling with the pressure control system.

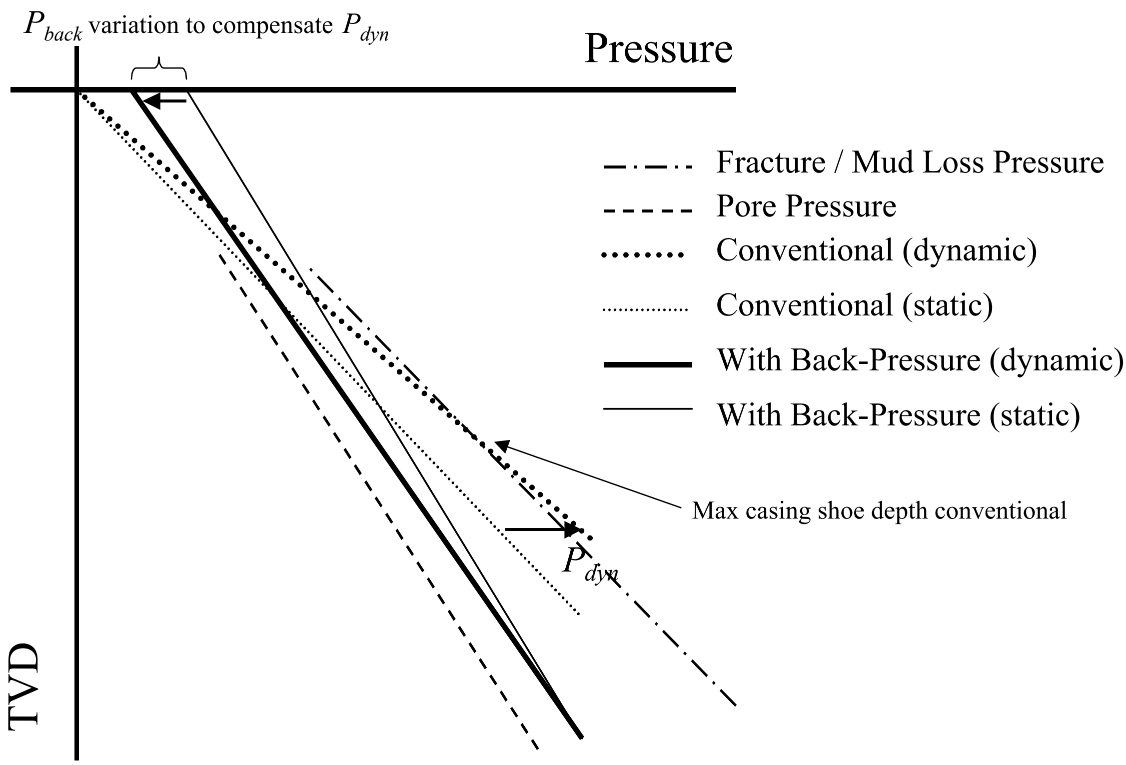

Fig.1b. Illustration dynamic pressure compensation with the pressure control system.

Fig. 2a. Custom built choke manifold installed on test site with control cabin in background.

Fig. 2b: Choke manifold and back-pressure pump installed on SimWell test facility.

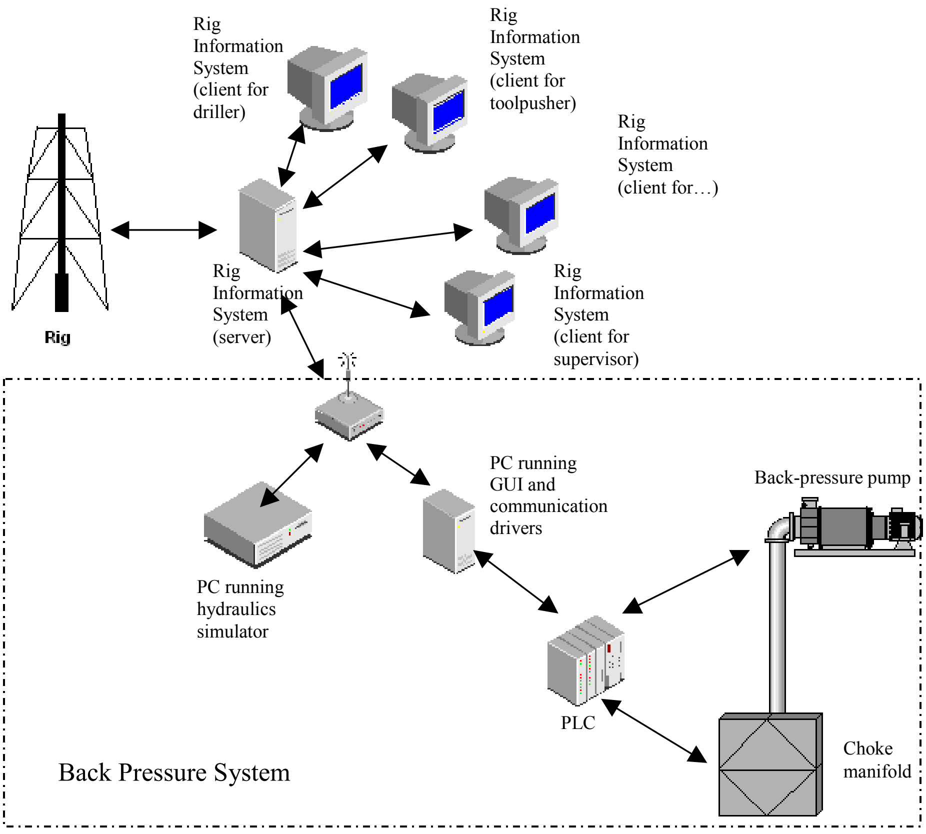

Fig. 3: Illustration working principle control system.

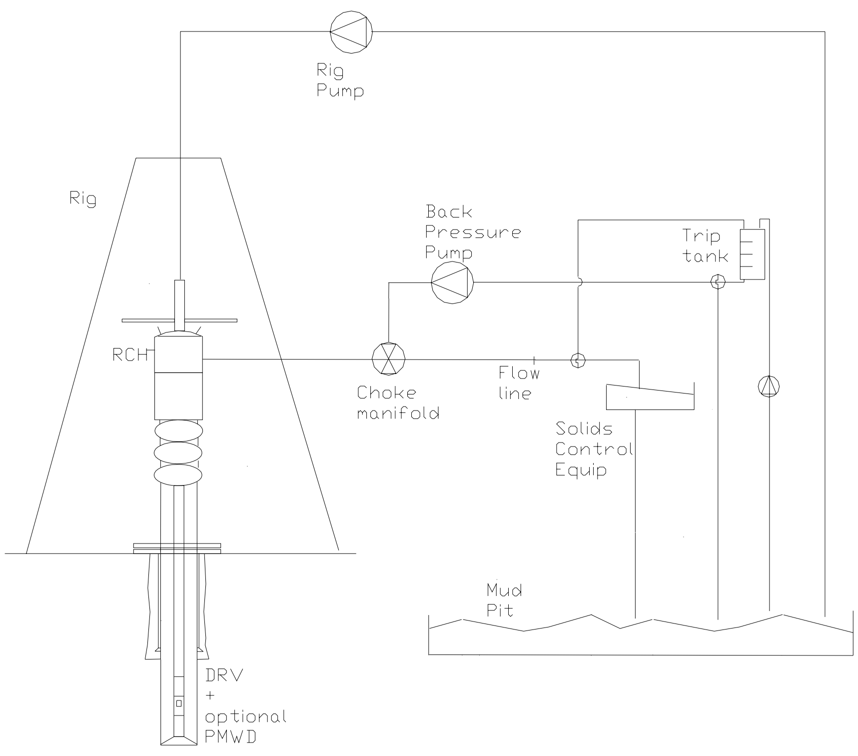

Fig. 4: Schematic typical rig installation back-pressure system.

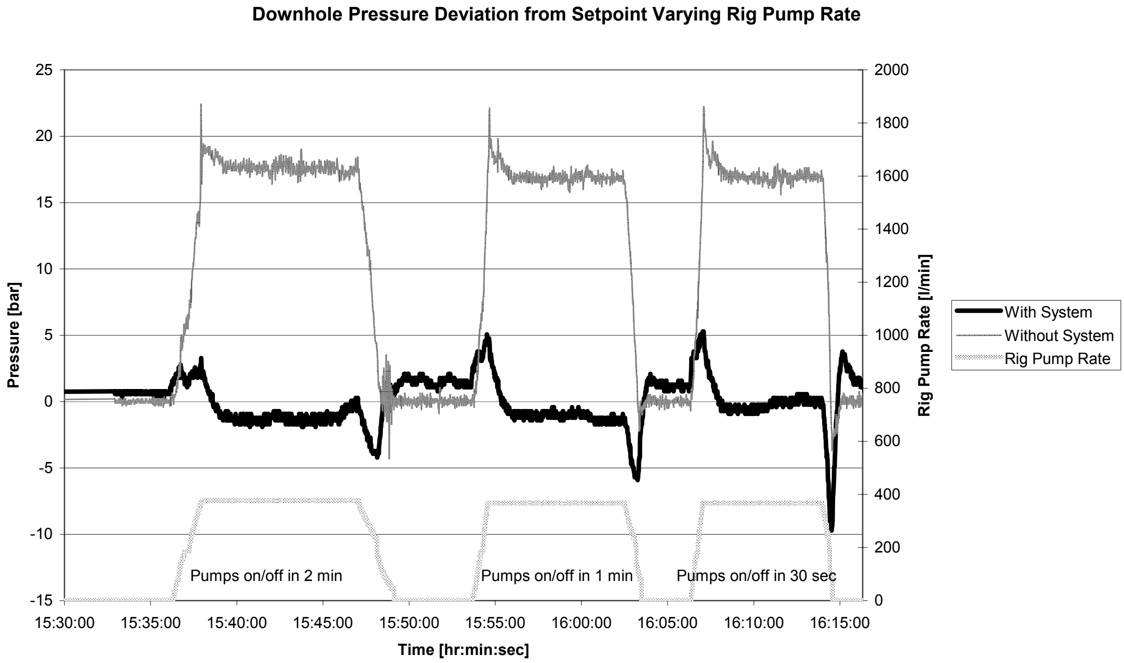

Fig. 5: Performace benchmark test

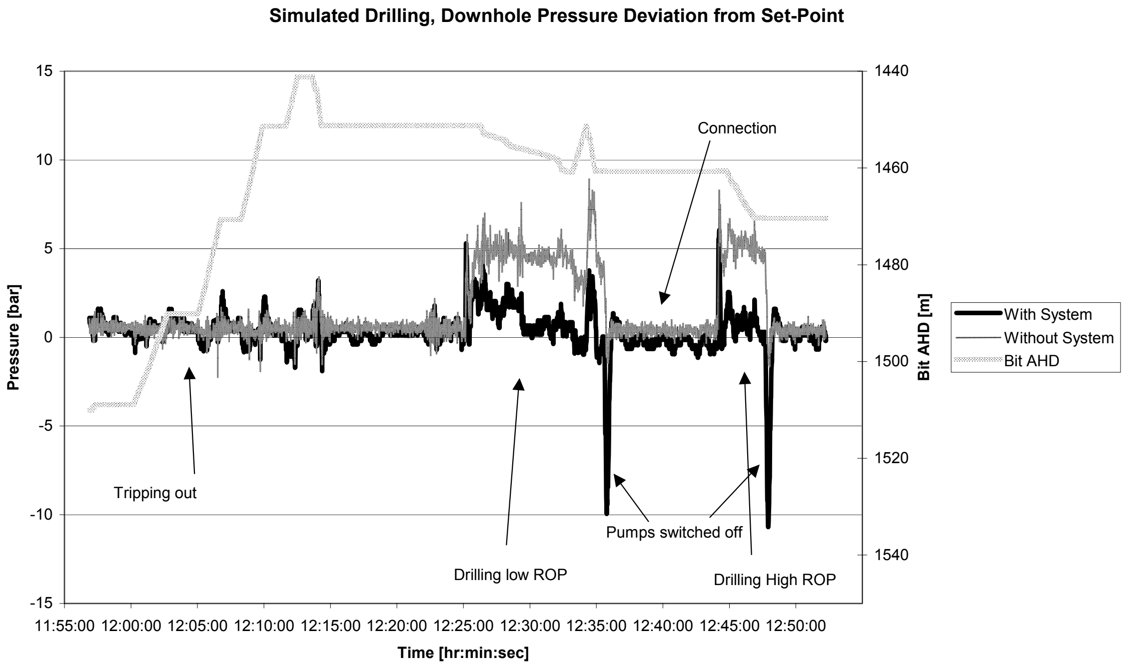

Fig. 6: Simulated drilling test results.

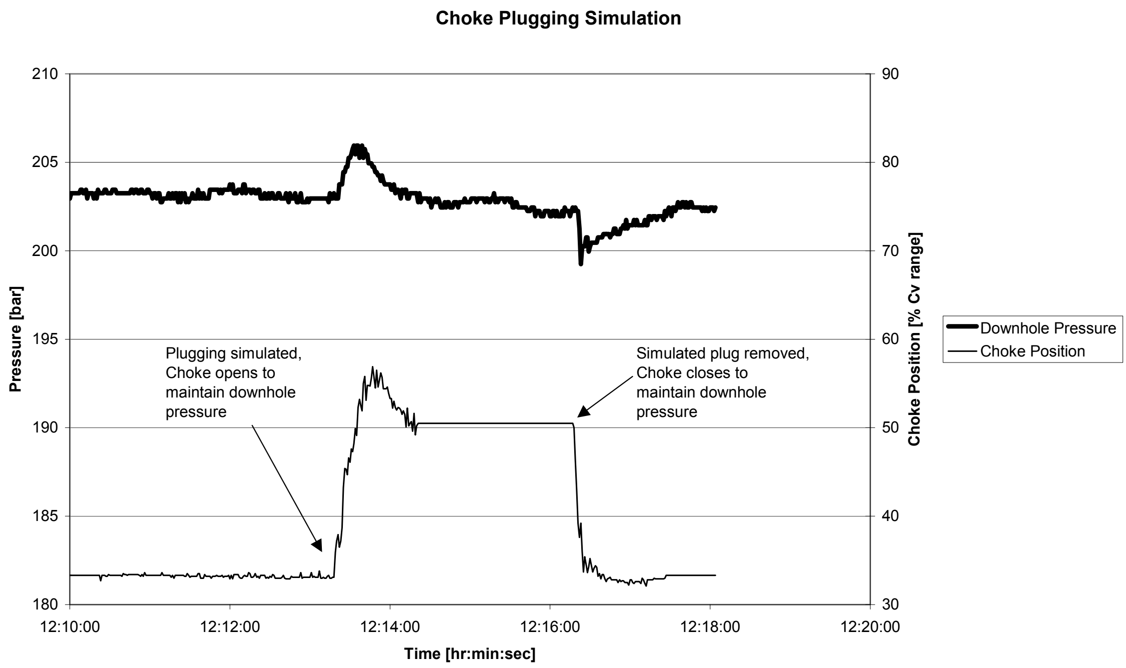

Fig. 7: Drilling problem test: choke plugging.

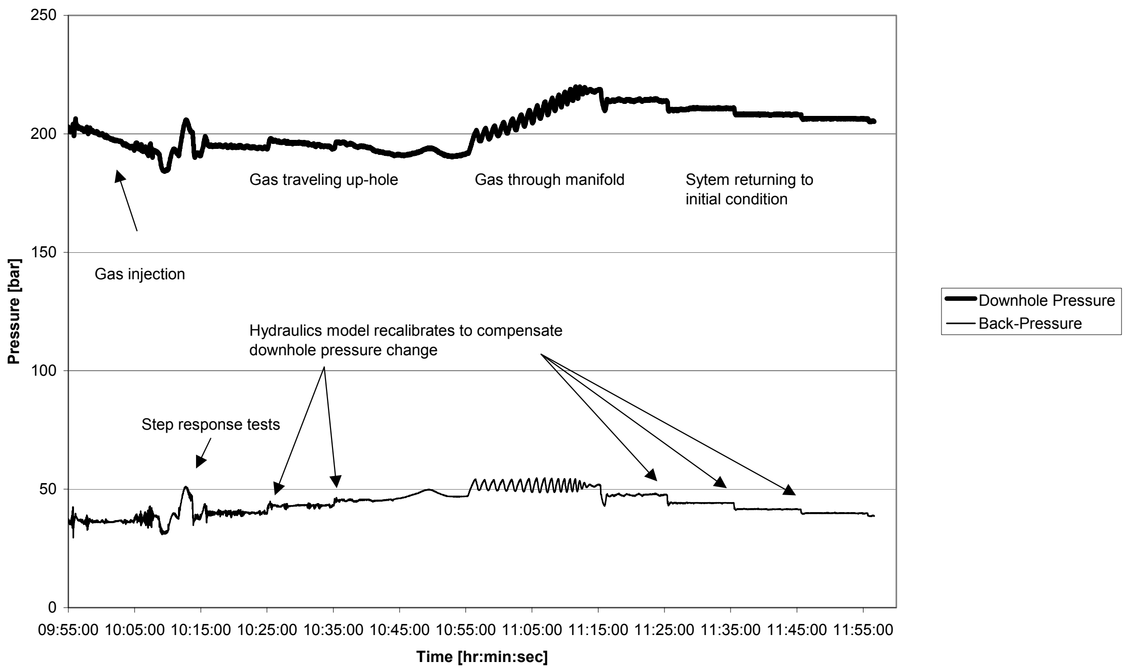

Fig. 8: Undetected gas kick.

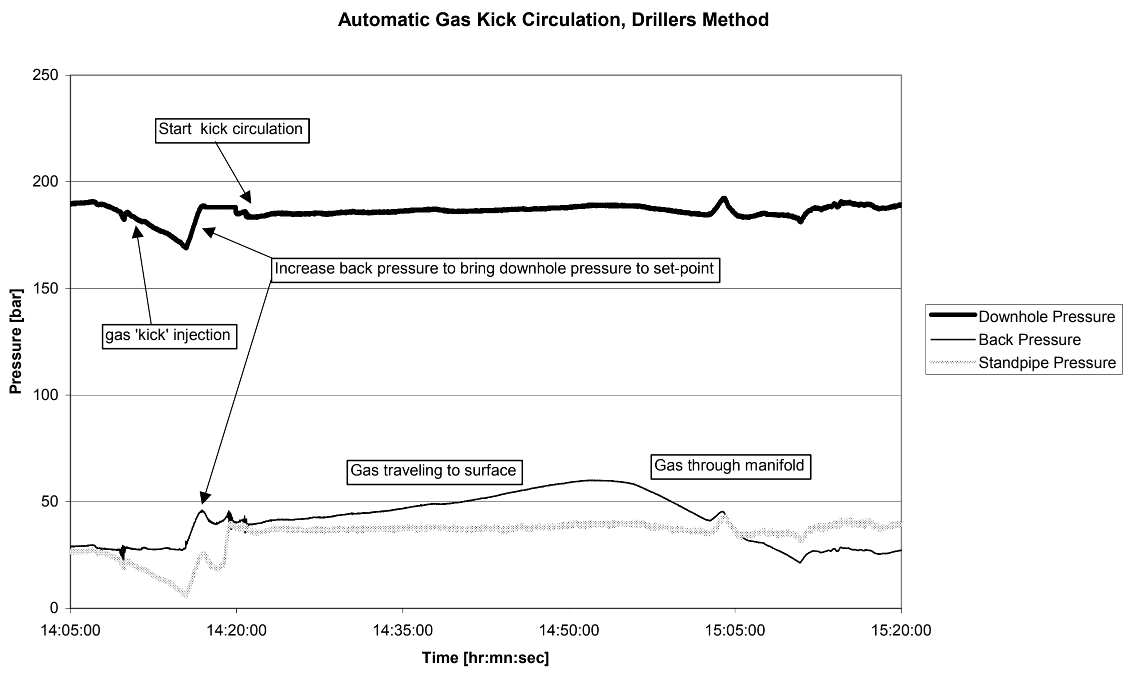

Fig. 9: Automatic gas kick circulation, drillers method.

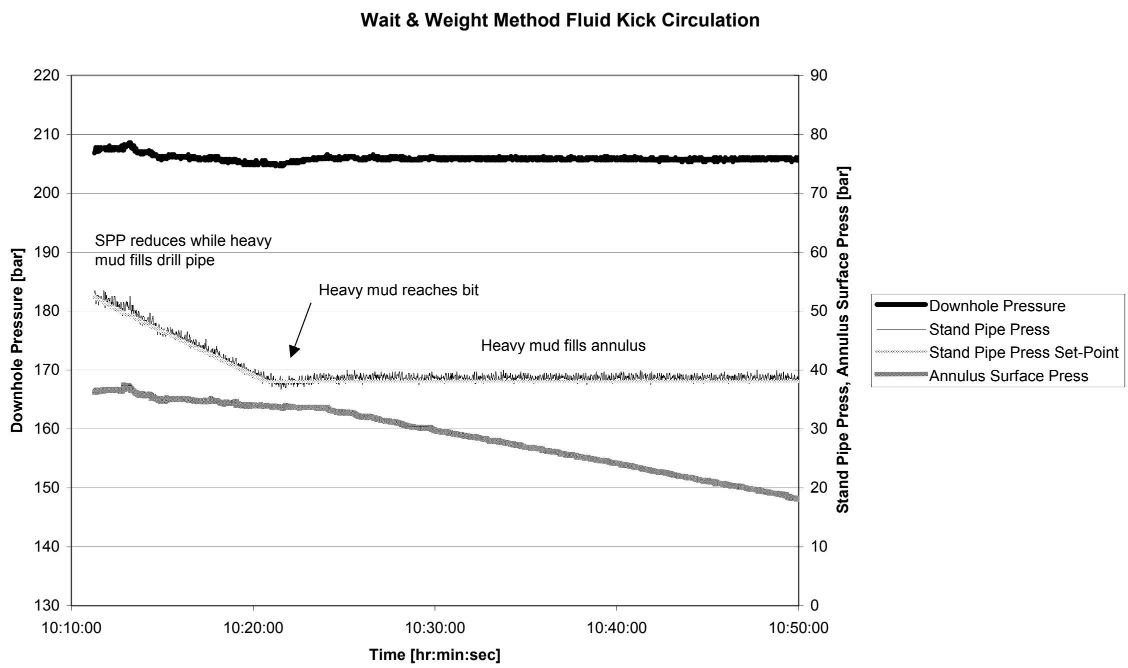

Fig.10: Wait & Weight method.