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Automatic Monitoring and Control of Annulus Bottom Hole Pressure for Safe Oil Well Drilling Operations

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Smart wells and real-time analysis are research tools that significantly increase robustness and safety, during oil well drilling operations. The major objective of this paper is monitoring and controlling an experimental drilling plant, through diagnosing and implementing decision making, for a desired operational window, despite the commonly observed disturbances that produce fluctuations in the well pressure. In fact, as the well is drilled, the hydrostatic pressure increases because of the well length grow. In addition, the reservoir fluid influx changes the well flow rate and density of the well fluid mixture. Finally, the pipe connection procedure, which requires stopping and starting of the drill fluid, produce severe fluctuations in the well flow rates. At deepwater and pre-salt layer environments, complex situations frequently occur, imposing a narrow operational window as a constraint. The main objective is under-balanced drilling implementations, that is, the well pressure is lower than the reservoir pore pressure and the reservoir fluids migrate into the well annulus (kick). During a blow-out (uncontrolled kick), large amounts of the reservoir fluids penetrate the well up to the surface, which may cause accidents and severe disasters. As a result, well construction is a complex process in which annular pressures must be kept within the operational window. In this scenario, this paper presents monitoring and control methodologies for annulus bottom-hole pressure, to avoid fluctuations outside the operational window limits, in order to guarantee safe conditions during the drilling operation.

1. Introduction

A drilling system consists of a rotating drill string, which is placed into the well. During oil well drilling, the bit alters the state of stresses inside the formation and the existence of low competency rock structures may produce instabilities. The material removed by the drilling process (cuttings) is placed by the drilling fluid, which tries to restore the previous equilibrium. If equilibrium is not attained, some type of rupture (fracture and collapse) is generated. Fractures are associated with the rupture of rock material (traction rupture), while collapses are produced due to the shearing produced by an unequal par of stresses around the well (compression rupture) (Perez-Téllez et al., 2004). The drill fluid is pumped through the drill string and exits through the choke valve. Due to well intrinsic geometry, the presence of the drill fluid produces a pressure gradient along the well length. The pressure balance between the well section and the reservoir is primordial for operation and security purposes. If the pressure in the well is higher than the reservoir pore pressure (over-balanced drilling), the circulation fluids penetrate into the reservoir, damaging formation and reducing well productivity. On the other hand, if the pressure in the well is lower than the reservoir pore pressure (under-balanced drilling), the

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reservoir fluids migrate into the well annulus. Over-balanced drilling is the most used method for drilling oil wells, for minimizes the risk of blow-out, which causes large amounts of the reservoir fluids to penetrate into the well and follow the well to the surface. During oil well drilling, the pore pressure (minimum limit) and the fracture pressure (maximum limit) define mud density range. As a result, the drilling fluid hydrostatic pressure needs to be higher than pore pressure, in order to avoid formation fluid invasion into the well. Simultaneously, the drilling fluid hydrostatic pressure needs to be smaller than fracture pressure, for avoiding formation damage.

2. The experimental drilling unit

The well drilling unit (Figure 1) was built using a drill string of 2.8 m, containing on-line flow – density sensors (Metroval - RHM20), based on Coriolis effect and an on-line pressure transducer (SMAR - LD301-M). The unit has two feeding tanks - water (8 ppg) and mud (15 ppg – pseudo plastic behaviour, Fig. 3), making feasible the annulus injection of varying solid concentrations, which in fact represents the implementation of different rates of penetration. A mud pump (Weatherford - 6 HP) connected to a frequency inverter (WEG), a choke line (choke valve – ASCO - 290PD-25MM) and butterfly valves (Bray – series30/31) connected to the feed tanks (rate of penetration) are the experimental unit manipulated variable candidates that may be used for controlling annulus bottomhole pressure. In addition, a computational program was built in order to monitor and control the drilling unit, using C++ language. Figure 2 presents the window program containing the controlled variable (pressure), the manipulated variable (flow), the set point and parameters of the classic type controller (PID) and the choke valve operational level.

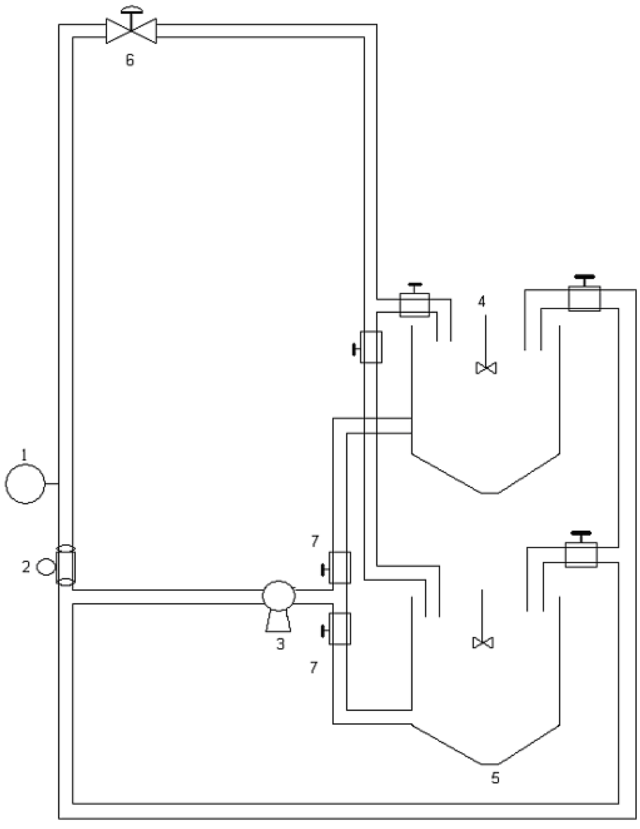


Figure 1: Experimental unit: 1 – pressure transducer; 2 - on-line flow and density sensor; 3 – helicoidally positive displacement pump; 4 - feed tank (density - 8 ppg); 5 – feed tank (density – 15 ppg); 6 – choke valve; 7 – butterfly valve.

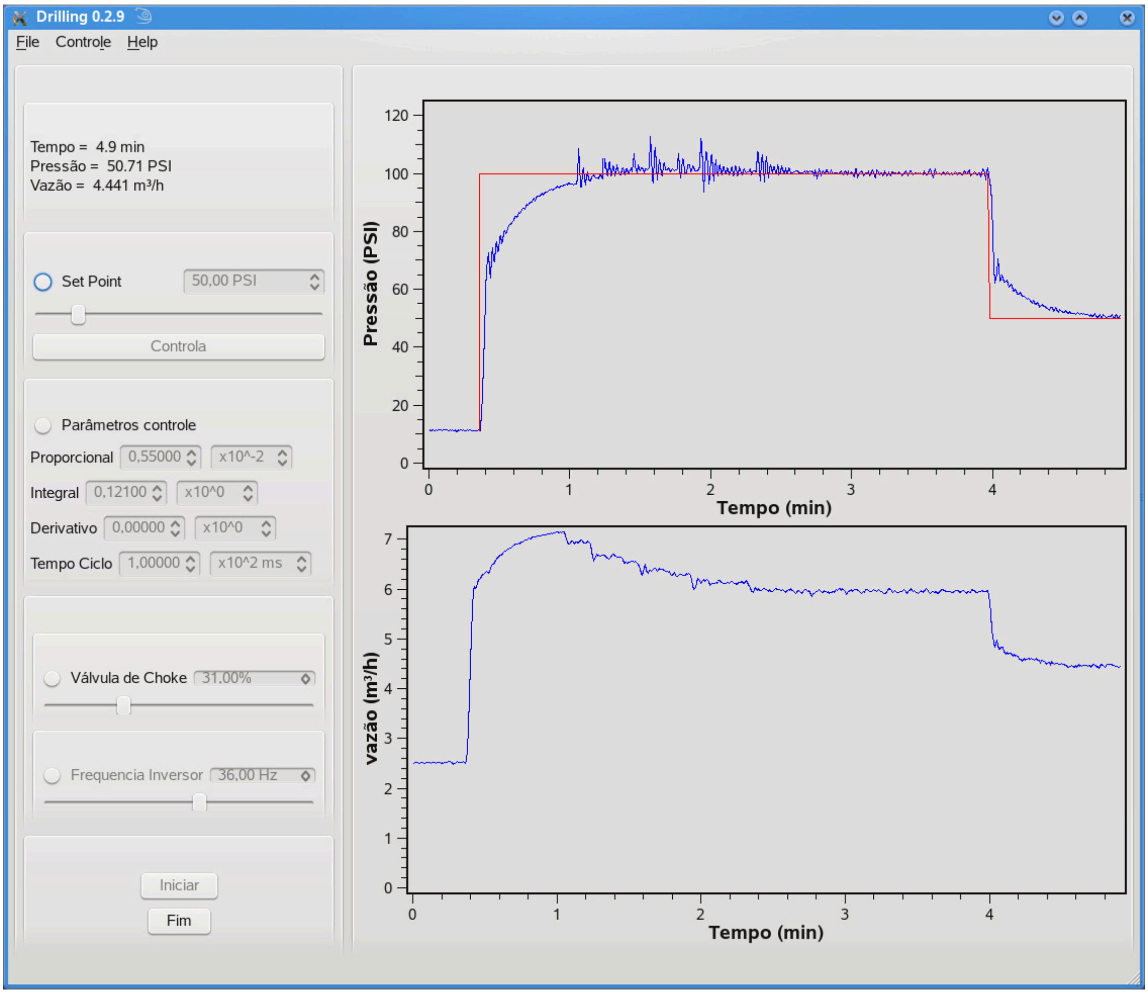
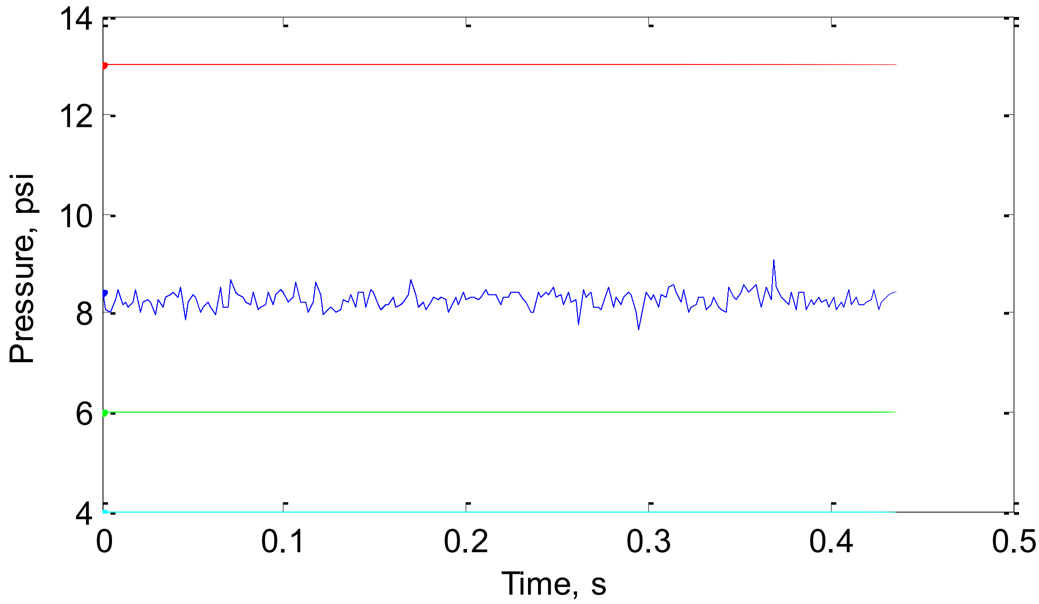


Figure 2: Monitoring and control C++ computational program.

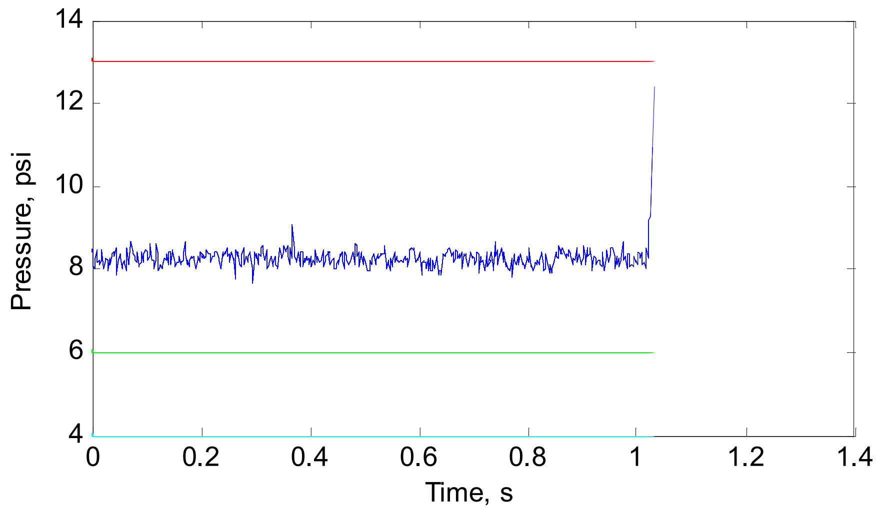
3. Monitoring scenario

A methodology using real time monitoring was built for diagnose and implement decision making for the oil well drilling plant. A computational program was developed in order to provide safe drilling inside operational window, that is, above pore pressure and below fracture pressure. Different experimental scenarios were analyzed and qualitative actions were recommended in order to regulate annular pressure (Figures 3-5). As can be observed through Figure 3, the monitoring program indicates that the process is operating regularly inside operational window. Next, a disturbance which produces an increase of annulus pressure is detected and the program suggest that choke valve opening index must be increased and/or pump flow rate must be decreased (Figure 4). The last scenario presents the program suggestions concerning operation outside the safe pressure envelope (above fracture pressure), indicating that fluid density must be reduced and a lost circulating material should be introduced in the system, more over, critical measurements may also be necessary, like for example, squeezing a cement plug (Figure 5).



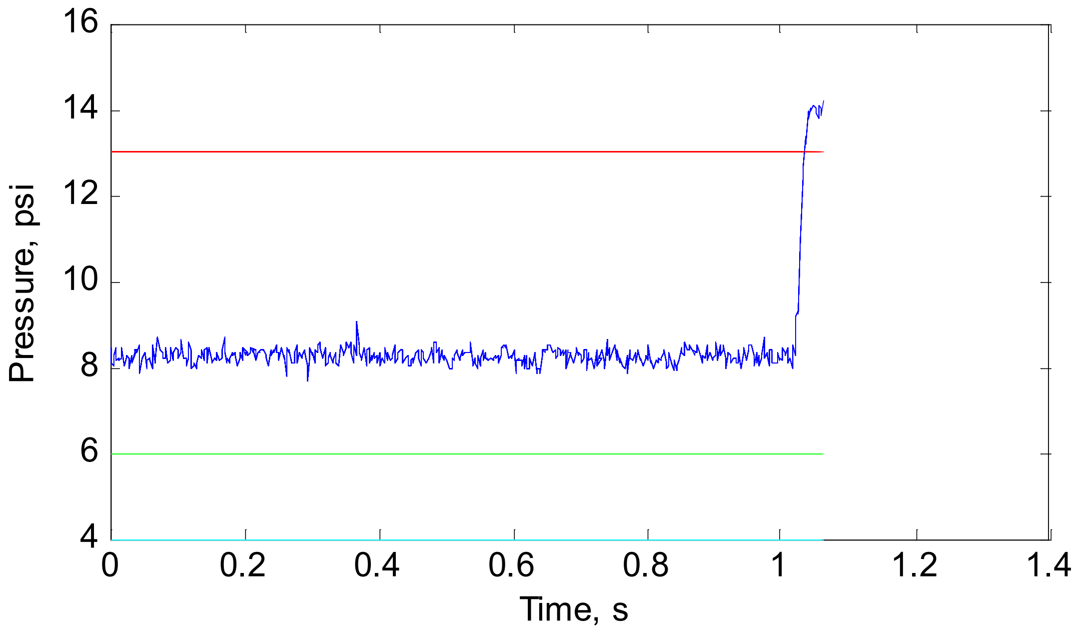
Process operating regularly
Pressure inside the safe operational window envelope

Figure 3: Operation inside safe pressure envelope; Red line: Fracture pressure; Green line: Pore pressure; Cyan line: Collapse pressure.



Process is approximating the fracture pressure
As a result: increase choke index and/or decrease pump flow

Figure 4: Qualitative suggestions for operation inside safe pressure envelope; Red line: Fracture pressure; Green line: Pore pressure; Cyan line: Collapse pressure.

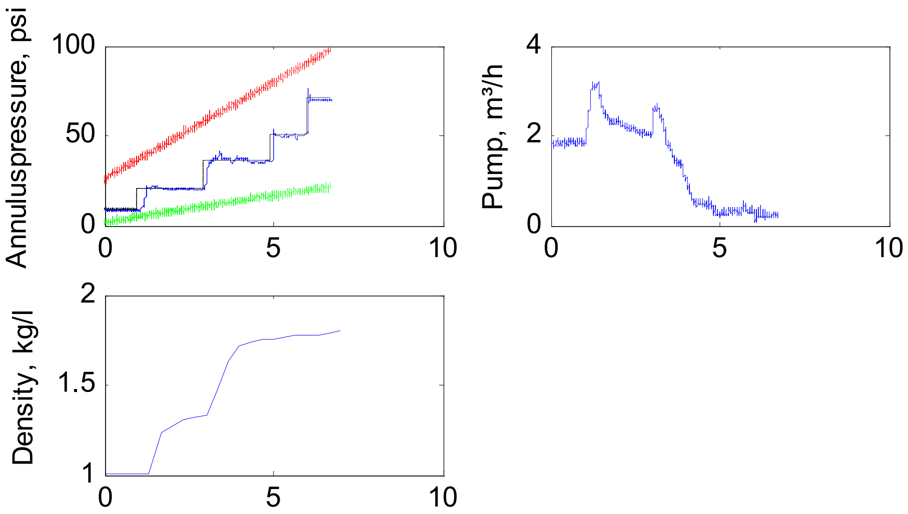


Process is above the fracture pressure
As a result: Reduce fluid density and inject lost circulating material
Critical measures: Squeeze a cement plug

Figure 5: Operation outside safe pressure envelope; Red line: Fracture pressure; Green line: Pore pressure; Cyan line: Collapse pressure.

4. Control scenario

For real time control methodology implementation purposes, non linear analysis (step test), plant identification and controller parameter estimation were performed over different operational levels. The methods of reaction curve (Ziegler-Nichols, 1942; Sundaresan and Krisnaswany, 1977) were employed in order to identify oil well drilling unit. An experimental controller was built in order to guarantee inside operational window drilling path. PI controller parameters, for different operational levels, were developed, through a priori implementation of reaction curve (Ziegler-Nichols, 1942) and the Sundaresan and Krisnaswany (1977) identification methodology, using the strategies of Ziegler-Nichols (1942) and Cohen-Coon (Cohen-Coon, 1953).
Servo control test concerns the implementation of a set point change for annulus pressure, which must be tracked through manipulated variable moves (pump flow or frequency inverter devices). Pump flow is varied according to the controller parameters fed to the C++ computational program, which remotely operates the plant, using a sampling time of 0.1 seconds. Figure 6 illustrates the successful servo and regulatory control tests implementation, using 15 ppg mud as the drilling fluid, assuring drilling conduction inside operational window, between pore pressure (minimum limit) and fracture pressure (maximum limit). The regulatory control tests were successfully implemented through introducing a plant load disturbance in the rate of penetration levels, which were experimentally produced by changing the drilling fluid from water to a 15 ppg drilling mud.



Objective: Operation inside pressure envelope
Controlled variable: Annulus pressure
Manipulated variable: Pump flow (Pump)

Figure 6: Servo and regulatory control tests; Red line: Fracture pressure; Green line: Pore pressure.

5. Conclusions

An experimental unit was built for analyzing recurrent phenomena that occur during the oil well drilling process. The experimental plant contained on-line flow – density sensors (Metroval - RHM20), pressure transducer (SMAR - LD301-M), two feeding tanks, mud pump (Weatherford - 6 HP), choke valve (ASCO - 290PD-25MM) and butterfly valves (Bray – series30/31) connected to the feeding tanks. Suggesting qualitative actions, a monitoring program was developed in order to assure operation inside pressure envelope, between pore and fracture pressure. A non linear analysis (step test), plant identification and controller parameter estimation were implemented over different operational levels. An experimental controller was built in order to guarantee inside operational window drilling path and disturbance (rate of penetration fluctuations) rejection.

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