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WELL CONTROL IN DEEPWATERS – A REVIEW

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Abstract. *Recent deepwater and ultra-deepwater hydrocarbon discoveries have driven an enormous effort of the scientific and technological communities to solve inherent problems associated with the exploitation phase. Widely used drilling pratices have been re-evaluated and optimized and new technologies have been developed to handle specific issues related to deepwater and ultra-deepwater drilling operations, such as reliable and efficient well control practices and high friction loss due to long kill and choke lines. This effort has great importance to some countries like Brazil, which have the major part of their oil and gas produced from offshore wells. The Campos Basin, located at southeast of Brazil, produces more than 70% of Brazilian oil and gas; and more than 70% of those reserves are located in water depths greater than 400m. Regarding such scenario, this article presents a comprehensive and discussed literature review about well control in deep waters. It comprises three parts: i) a review regarding well control procedures and techniques, including the selection of well killing and well control methods; ii) a general overview of two-phase flow models in vertical, horizontal and deviated wells; and iii) a review of mathematical kick simulators including theoretical considerations and capabilities of numerical and analytical models available.*

Keywords: *deepwater wells, well control, drilling*

1. INTRODUCTION

The exploitation in deepwater and the development of concepts related to this activity has been changing a lot throughout the years. In the sixties, for example, the exploitation and the development of offshore fields used to be restricted to water depths with 46m. The biggest challenge in that time was to exceed the limit of 50m. Nowadays, depths with 400m are considered as deepwater and above 1000m are considered as ultra-deepwater (Ohara, 1996).

In these days, Brazil is one of the leaders in drilling and production in deepwater. This leadership is due to the fact of 75% from the national production is located at the Campos Basin, in the north coast of Rio de Janeiro, being 73% of the reserves located in deepwater and ultra-deepwater (Martins et all, 2000). The drilling activities in deepwater in Brazil were estimated by the discovery of the Albacora's field, in 1984, in a water depth that varies from 293 to 1900m. In 1985, Marlim's field was discovered through the well RJS-219, with 823 m of water depth.

In 1994, the Marlin-4 well, with 1027m, was completed and its production was started. In 1996, the giant field of Roncador was discovered, with water depths varying between 1500 and 1900m.

The world's record of water depth nowadays is the 1-RJS-543, located at Roncador's field, reached in November 1999 with 2777m.

In the drilling operations in deepwater, an accurate control of all the drilling parameters, added to a well detailed project and program are factors of extreme importance in the environmental, economic and security aspects. A permanent concern in these operations is the control of kicks and the prevention of blowouts.

2. KICK DEFINITION AND CONTROL METHODS

Kick is an undesirable influx of the fluid from the formation to the well's inside. Once the kick is detected, the well must be closed and the incoming fluid must be circulated to the outside of the well. If before or after the circulation of the kick the control of the well is lost, there is a situation of blowout, in which the influx reaches the surface, what might cause serious accidents. Although the majority of the kicks is controlled, an occasional blowout may result in several losses of equipments and even the well, as well as the loss of human lives. In offshore scenarios, blowout situations are more critical, due to the safety of the rig crew and the risk of environmental damages.

2.1. Methods of Kick Control

The methods of well control consist in circulating the influx to the outside of the well keeping the pressure inside of it bigger than the pressure of the formation, aiming to avoid additional influxes. The detection of an influx is normally done through the volume increase of the drilling fluid tank (pit gain). In a practical way, we can specify a volume raise to the first alarm, in order to permit preventive actions before the situation becomes critic. Once the kick is detected, the well must be closed.

The two main closing methods are:

- Hard Shut-in: In this method, the choke (safety valve on the outside line of the wellhead) must be closed when the BOP closes (Blowout Preventor); and
- Soft Shut-in: The choke is open when the BOP closes.

Lage *et al* (1994) showed that the soft shut- in method, as well as the flow-check procedure (the mud bombs are turned off to observe the occurrence of mud flux on the surface), cause an additional influx, due to the delay to the well shutting and must be avoided.

The main methods of kick control are:

- Driller's Method: it consists in expelling the incoming fluid first using the original drilling fluid (mud), and afterwards bombing new mud until fill the well;
- Wait and Weight Method (Engineer's Method): the circulation of the incoming fluid is done with new mud, that is, after the weight increase is done.
- Simultaneous Method: it consists in the progressive and gradual increase of the mud weight in parallel, in the circulation of the invading fluid, until the weight of appropriate new mud to the control of the formation that caused the kick is reached.

The driller's method is more used because of its simplicity. The wait and weight method is more complex and depends on the new mud availability to be injected.

3. TWO-PHASE FLOW MODELS APPLIED TO THE STUDY OF KICKS

The development of a reliable mathematical model of kicks, that presents results the closest as possibly to the reality, demands a proper modeling of the two-phase flow, concerning vertical, ascendant, deviated or horizontal flows. The ascendant vertical two-phase flow is useful to models in which is adopted a scenario of vertical well. On the other hand, the horizontal two-phase flow is useful for kick models that consider horizontal wells or slightly deviated ones.

The knowledge of two-phase flow models in ducts and horizontal and deviated annular spaces (annulus) has a great importance to the development of kick models in horizontal and directional wells, considering the big number of directional wells drilled nowadays.

Rader, Bourgoyne and Ward (1975) made an experiment in a training well LSU B-7, in Louisiana State University, with the objective to determine the factors that affect the migration speed of a gas kick in annular space. Mixtures of glycerin/water and gum/ water were utilized to simulate the drilling fluid, and nitrogen was utilized to simulate the gas influx. They figured out the correlation that calculates the gas speed in the annulus using the single bubble model showed in Fig. (1). The final correlation is given by Eq. (1),

$$v_b = (0{,}163 + 0{,}092 \cdot \log N_{rb}) \cdot (d_1 + d_2)^{1/2} \cdot \left(\frac{\rho_m - \rho_g}{\rho_m} \right)^{1/2} \tag{1}$$

where d_1 and d_2 are respectively the external diameter of the internal duct of the annular space and the internal diameter of the internal duct, ρ_m is the mud density and ρ_g is the gas density.

With $1 < N_{rb} < 100.000$ and N_{rb} is given by Eq. (2),

$$N_{rb} = 928 \cdot \rho_m \cdot \frac{v_b \cdot (d_2 - d_1)}{\mu_m} \tag{2}$$

Where μ_m is the mud viscosity.

Rader, Bourgoyne and Ward concluded that the migration speed, as much as fragmentation of the bubbles, have significant influence in the pressures in the annular space during the kick circulation.

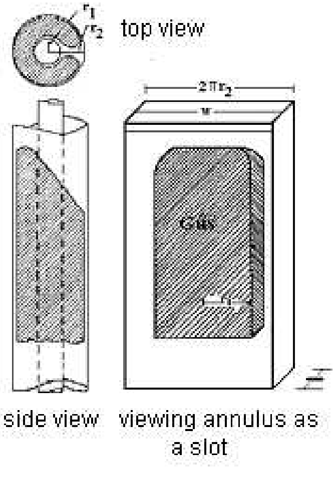

Figure 1. Assumed Model for A Gas Bubble Raising Through the Annular Space (Rader *et al*,1975).

The factors that affect significantly the speed of the gas migration are the internal and external radius of the annulus, viscous characteristics of the liquid, densities of the liquid and the gas, gas expansion and the speed of the liquid. Therefore, factors such as the bubble length, superficial tension between the gas and the liquid and the eccentricity of the annular space don't perform considerable effects in the speed of the gas migration.

Stanbery (1976) proposed the utilization of an uniform distribution of gas inside the drilling fluid. In this distribution, the bigger bubbles, for having a bigger speed, stay in the superior part, while the smaller ones stay in the inferior part, as showed in Fig. (2).

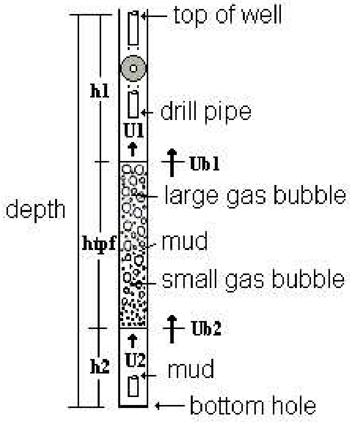

Figure 2. Kick Distribution of the Annular Space (Stanbery, 1976).

The Griffith correlation (1964) to evaluate the bubbles speeds is used, obtaining a correlation given by Eq. (3),

$$v_b = K_1 \cdot \sqrt{\frac{g \cdot d_e \cdot (\rho_l - \rho_g)}{\rho_l}} + (1 + K_2) \cdot v_m \tag{3}$$

where v_m is the mud speed, v_b is the bubble speed and the factors k_1 and k_2 are obtained in function to the ratio between the internal and external diameters of the annular space.

Taitel, Barnea & Dukler (1980) suggested transition mechanisms among flow patterns in vertical ducts. Figure (3) shows a map of a flow pattern developed from the suggested mechanisms.

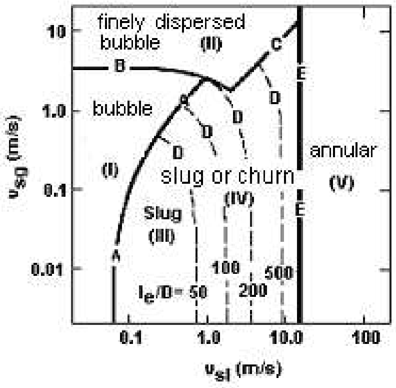

Figure 3 - Map of Ascendent Vertical Flow Patterns in Ducts for An Air-Water Mixture (Taitel, Barnea and Dukler, 1980).

Caetano (1986) defined maps of flow patterns, based in Taitel, Barnea and Dukler's model (1980), getting a good correlation to the prevision of the flow pattern and of the pressure gradient in vertical two-phase flow for concentric and eccentric annulus. He made experiments with water-kerosene mixtures and used the same classification from the flow pattern applied to ducts. Fig. (4) shows the patterns of vertical two-phase flow in eccentric annulus.

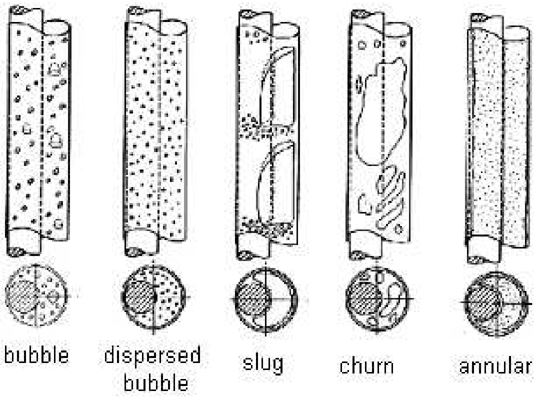

Figure 4 - Vertical Two-Phase Flow Patterns in an Eccentric Annular space (Caetano, 1986).

Nakagawa (1990) carried out an experimental study of eccentric flow in different inclinations angles (deviations) to determine the gas fraction and the speed of the gas during the kick. Values of 0° (vertical), 10°, 20°, 70° and 80° were adopted. Nakagawa's model gives good results for gas-water mixtures, but it does not provide good results to the gas-xantana gum mixture.

Johnson and White (1991) carried out some experiments to study the rise speed of the gases in ducts during kicks. They have used water and xantana gum as the liquid phase and air as the gaseous phase. This represented an extension of the existent correlations to the two-phase flow in ducts of big diameters, utilizing non-newtonian fluids.

The results show that the gas rises faster than what was previously expected, because the speed of Taylor's bubble considers the parcel of the liquid speed. This has a bigger implication in the kick simulation, with gas reaching the surface faster than what was expected and the gas outside flowrate bigger than expected.

Johnson and Cooper (1993) investigated the effects of the well deviation and geometry in the speed of migration. They extended Couet's *et all* (1987) model with the objective of encompassing the effects of a concentric body with radius r in the flo, as presented by Eq. (4),

$$v_t(\theta,r) = v_t(\theta)\cdot\left(\frac{1+\dfrac{r}{\pi}}{1+\dfrac{\sqrt{2}\cdot r\cdot(sin\theta)}{\pi}}\right) \tag{4}$$

where r is the well radius, θ is the well deviation and $v_t(\theta)$ is the migration speed obtained in the Couet's *et all* model (1987).

For the vertical wells ($\theta = 0^o$), they concluded that for the flow in duct and in annular space the migration speeds of the gas are very close. To the vertical orientation, the distribution coefficient of the gas is the same, while the slippage speed is slightly bigger in the annular geometry.

In deviated wells, the distribution coefficient of the gas is bigger for the annulus and the slip speed is slightly bigger in ducts. For a deviation above 45° the slip speed becomes constant. According to them, even without mud circulation, the gas migrates in a speed above 0,5 m/s.

3.1. Sumary of the Main Two-Phase Flow Models Used in the Study of Kicks

The evolution of two-phase flow models has contributed a lot to the studies about well control. The development of correlations for the determination of the migration speed of the gas in vertical, horizontal and deviated annular spaces, besides experimental studies carried out to investigate the phenomenon of gas migration in non-newtonian fluids have been the main contributions in the most recent models.

4. MATHEMATICAL MODELS OF KICKS

The first mathematical model of the kick circulation was proposed by LeBlanc and Lewis (1968). This model disregards the pressure loss by friction in the annulus, the slippage speed between the gas and the mud, a uniform annulus capacity and the gas insolvable in the mud. The Fig. (5) shows the comparison from the results of the model with the results achieved in the field.

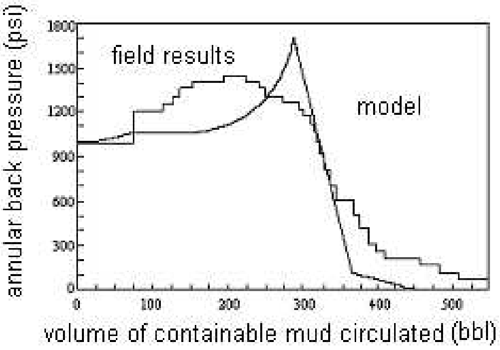

Figure 5 - Comparison Between LeBlanc and Lewis’s Model and Data from the Field (LeBlanc and Lewis, 1968)

Records (1972) improved LeBlanc and Lewis’s model, incorporating the effect of friction loss in the pressures behavior of the in the annulus. Even though, there was an improvement in LeBlanc and Lewis’s model, Records’s model presented results very far from those observed into practice, because this model didn’t considers the slip speed between the phases.

Hoberock and Stanbery (1981) proposed a model that simulated a dynamic behavior, incorporating the movement equations that describe the pressure in a vertical line and with a constant sectional area. They adjusted the properties of the two-phase flow as medium properties, in a way that they could consider the two-phase flow as a single-phase flow. They used the Griffith’s (1964) correlation and a flux pattern in bubbles. Figure (7) shows the comparison of the results achieved by Hoberock and Stanbery and the data achieved in field.

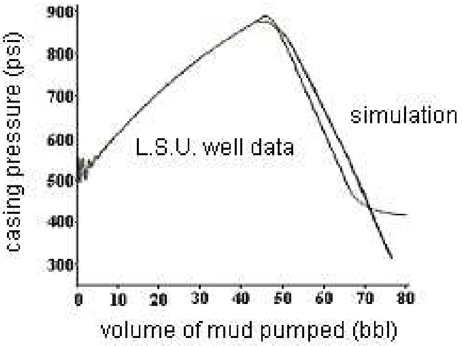

Figure 7 - Comparison between the simulator and the field data (Hoberock and Stanbery,1981)

Santos (1982) developed a mathematical model for kick circulation in deepwater considering the slip between the gas and the drilling fluid, the friction losses in the two-phase region and the void fraction. The model also considers a pattern of bubbles in the two-phase region and a constant well geometry. The Orkiszewski’s method (1967) was used to the calculus of friction losses in the two-phase region, considering the power-law model for the mud.

According to Santos, the gas density, the geothermal gradient and the minimum diameter of the gas bubbles cause a minimum effect in the circulation of the kick. Variables as the initial medium fraction of a gas, the well geometry, the water depth, the diameter of the choke line, and the mud rheologic parameters exert a moderate effect. On the other hand, the initial volume of the influx and the specific mass of the drilling mud exert a great effect during the circulation of the kick.

Nickens (1987) presented a model based in the balance equations of mass for the mud and for the gas, in the balance equation of movement quantity for the gas-mud mixture, coming to an empirical correlation associating the gas speed with the medium speed of the mixture plus the slip between the phases, besides the state equations for the mud and for the gas. Nickens's model also considered the effects of the well geometry, the drillstring, bit, mud pumps, and the coupling with the reservoir.

Podio and Yang (1986) proposed a simulator of well control, based in Nickens's model (1987). The main difference between the two models is related to the solution method of the differential equations. While Nickens used a fixed grid, Podio and Yang used a solution with moving boundary.

Negrão (1989) developed a circular modeling of gas kick in floating rig located in deepwater, using correlations to the two-phase vertical flux of the liquid/gas. To the single-phase region, he used the rheologic model of Bingham to characterize the mud. The model foresees the pressure in the choke line and in the region of the annulus during the kick control. It was used Beggs-Brill's correlation (1973) for the calculus of the friction loss in the two-phase region.

Santos (1991) proposed a mathematical model for control in horizontal wells, based in Nickens's model (1987). This model foresees the pressure behavior in the annular space, during the circulation of the kick in the well. It is also presented a simplified theory for the swabbing effect during the drillstring pull-out from the well and the risks of taking a kick during this kind of operation are demonstrated.

According to Santos, a horizontal well has a bigger tolerance to the kick during the well closing. That's why it's reasonable to conclude that the possibility of a casing shoe fracture when well closing is smaller in horizontal wells.

Ohara (1996) developed a kick simulator for deepwater wells, that has proved to be as fast, reliable and appropriate as the commercial simulators, besides the possibility of being available in the rig, through the use of a PC. This model is based in Nickens's studies (1987), which was divided in several sub-models, such as a one well sub-model, one from the gas reservoir, one from the choke and another from the rise speed of the gas through the well.

To elaborate the model of gas speed through the well, it was carried out an experimental work in an in real scale well at Louisiana State University, where natural gas was used as the gaseous phase.

Rommetveit and Vefring (1991) carried out performance tests of the model used in the simulator RF Kick Simulator from Rogaland Research (Norway). This simulator considers the more important physical effects, related to the kick as well as to the oil-based and water-based drilling fluids (muds). The data from the surface and bottom-hole data were achieved through an experiment in real scale, carried out at Rogaland Research Institute, in the Ullandhaug 2 well, that has a depth of 2000 m and has a 60º deviation.

Figure (8) shows the pit gain simulation and the experimental results comparison. It can be noticed the good adjust of the model's values.

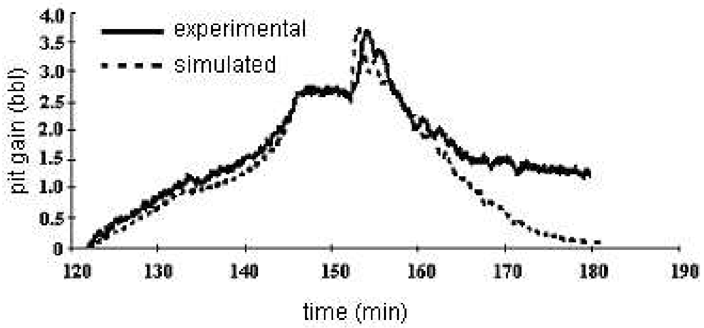

Figure 8 - Comparison of the Pit Gain (Rommetveit and Vefring, 1991)

4.1. Sumary of the Kick Mathematical Models.

The discovery of oil fields in greater water depths leads to a technological progress in deepwater drilling operations. Factors related to the equipment and personal security, environmental damage, besides financial factors are constant concerns in offshore operations. The accurate kick and blowouts control during the drilling operations in deepwater have been demanding a constant evolution in the simulators.

Lately, the progress of computers was also one of the essential factors for the evolution of kick simulators. Faster and more accurate hardware and software allowed the development of mathematical models each time more complex, considering hypothesis that were so far disregarded, due to machine limitations.

The incorporation of the effects of high friction loss and the gas expansion in the well, besides the slip between the phases have brought a huge contribution to the progress of the models, which started to provide better results than the first models. The development of correlations for the gas migration speeds have been significantly improved, with the incorporation of the effects of geometry and well deviation.

Aiming to acquire a more objective view of the model's evolution, the Tab. (1) joins the main features of each model.

Table 1. Main Features of the Models

Model Features	LeBlanc e Lewis (1968)	Records (1972)	Hoberock e Stanbery (1981)	Santos (1982)	Nickens (1985)	Podio e Yang (1987)	Negrão (1989)	Santos (1991)	Ohara (1995)
Deviated and horizontal well								X	
Two-phase Friction loss		X	Beggs Brill	Orkizewski	Beggs Brill	Beggs Brill	Beggs Brill	Beggs Brill	Beggs Brill
Slip velocity			X	X	X	X	X	X	X
Reservoir coupling					X	X		X	X
Well geometry	Constant	Constant	Constant	Constant	Variable	Variable	Variable	Constant	Variable
Circulating method	Driller's	Driller's	Driller's	Driller's	Driller's Engineer´s	Driller's Engineer º	Driller's	Driller's	Driller's
Drilling fluid rheology	Newtonian	Bingham	Bingham	Power-law	Bingham	Power	Bingham	Power	Bingham
Two-phase model	Single bubble	Single bubble	Bubble distribution	Bubble distribution	Bubble distribution	Bubble distribution	Bubble distribution	Bubble distribution	Bubble distribution

X = adequated

The simulators have been improved, mainly in the modeling of the two-phase region. Nowadays, the majority of the simulators consider the kick as a two-phase region of dispersed bubbles with a certain distribution. The calculus of the friction loss in the two-phase region has also developed, with the development of more complete correlations, applicable to wells with any kind of deviation and geometry.

5. Conclusions

The results of the studies about well control have been causing the increase of safety in the drilling operations making them less complex, faster and reliable.

The kicks simulators have permitted the prevision of the pressures behavior during the well control, being possible the prevention of accidents during drilling operations, which could cause serious material losses, environmental damages, and mainly the loss of lives.

Nowadays, the simulators are able to reproduce the most diverse scenarios of kicks, with oil-based and water-based drilling fluids, kicks in deviated and vertical wells, in shallow and deep waterdepths, providing satisfactory results. This evolution is due to the following factors:

- development of correlations to determine the speed of gas migration in non-newtonian fluids, considering variable annular geometries, different deviations, that shows in a satisfactory way a real kick situation.
- incorporation from the effects of friction loss and of the gas expansion and the consideration of slip models between the phases.
-The progress of computers, allowing the elaboration of more complex mathematical models, with reliable results in a smaller time of computational time.

6. Conversion Factors

bbl x 1,589873 10^{-1} = m^3
in ou pol. x 2,54 10^{-2} = m
psi x 6,894757 = kPa
lb/gal x 1,198264 10^{2} = kg/m^3
ft/s x 3,048 10^{-1} = m/s
cP x 1 10^{-3} = N s/m^2

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