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TRANSIENT MATHEMATICAL MODEL FOR KICK DETECTION

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Abstract. *During well drilling operations, kicks must be detected as soon as possible in order to avoid any risk of blowout. However, due to the lack of instrumentation in drilling operations, kicks are still detected by the pit-gain, which usually takes place after a significant amount of fluid had invaded the well. Changes in the downhole and pump pressures, increase in the outlet flow rate and changes in the speed of sound may also indicate the formation influx. The current work presents a transient model to evaluate the changes in the pump and downhole pressures, outlet flow rate, pit-gain and speed of sound in order to detect a kick faster. The model is based on the mass and momentum balances applied to gas-drilling fluid mixture and also accounts the drilling fluid viscoplasticity and compressibility. The results of the model allow a better understanding of the parameters variations caused by a gas kick, which can improve the kick detection, increasing the rig safety and decreasing the costs of the well drilling operation.*

Keywords: *kick, pit-gain, compressibility, transient*

1. INTRODUCTION

The pressure control has a major importance in the drilling of oil and gas wells. The pressure must be kept within a range called as the operating window, which is defined by the maximum (fracture) and the minimum (pore) pressures. As the well depths have been increased in offshore oil exploration, the operating window size has been reduced. If the pressure inside the well is lower than the pore pressure, there is an underbalanced situation where kicks occur (Yin, *et al*., 2017). Kicks are the invasion of formation fluid into the wellbore. When the pressure is higher than the fracture pressure, the formation can be damaged. Whenever a kick occurs, it must be detected as soon as possible. Additionally, gas kicks are even more difficult to be handled because of the gas compressibility, and if not controlled in time, it can escalate to a blowout (Vajargah *et al.*, 2013). A faster gas kick detection reduces the amount of gas that enters the well, reducing the closing pressures and making the kick easier to control (Ahmed *et al.*, 2016).

During the well drilling, several parameters that are monitored can indicate the gas kick occurrence. Besides a decrease in the pump pressure, increases in the inlet and outlet flow rate, rate of penetration and pit-gain can also indicate that an influx is occurring (Ahmed *et al*., 2016).

The pit-gain is the level increase of mud in the tanks and is one of the most employed kick indicators (Islam *et al*., 2017). However, as the drilling fluid that returns from the annular space needs to pass through the cleaning process (Fraser *et al*., 2014), it takes minutes to begin the pit-gain after the kick has started. Furthermore, the pit tanks have big surface areas, measuring about 40 m², which means that is needed a significantly influx to be detected by the sensors. Also, the pitch and roll of floating rigs influence negatively the measurement of the mud level (Brakel *et al*., 2015).

The trip tanks are much smaller than the mud pits, therefore a measurement more precisely is performed in the trip tanks, but they only can be used when the well is not being circulated (Fraser *et al*, 2014). The outlet flow rate is measured by a flow-paddle located in the return channel from the annular space to the pit-tank, but it is an inaccurate flow measurement (Carlsen *et al*., 2013).

Several studies propose the gas kick detection by acoustics methods (Bryant *et* al., 1991; Stokka *et al*., 1993; Hage and Avest, 1994). During the circulation, pulses from the bottom hole are sent to the surface. These pulses travel with the speed of sound in the drilling fluid, varying from 1000 m/s up to 1500 m/s. The presence of free gas changes significantly the pressure-wave speed (Wylie *et al*., 1993; Chaudhry, 2014). At atmosphere conditions, the speed of sound can be reduced from 1500 m/s up to 50 m/s if 2-3% of gas is mixed with water (Stokka *et al*., 1993). Therefore, a delay in the time response of mud pulses can be a positive indicator of a gas kick.

The current work presents a transient mathematical and numerical model for a kick simulator. The model is based on the balance equations of mass and momentum applied to the gas-liquid mixture. The gas influx is modeled by the Darcy's law and the gas is considered as real. The variation of the pressure-wave speed due the presence of free gas is taken into account. Through the kick simulator it is possible to analyze the effect of gas influx on the pump and downhole pressures, outlet flow rate, pit-gain and time response of mud pulses. Therefore, the model can assist in the identification of a positive kick indicator and also it can identify the best indicator for a faster kick detection.

2. MATHEMATICAL MODELING

2.1 Governing equations

The developed model is based on the balance equations of mass and momentum applied to the mixture. The flow is considered as transient, laminar, isothermal and one-dimensional. The drilling fluid is compressible and the Bingham model is employed. The borehole compressibility and the rate of penetration are disregarded, therefore the well has constant dimensions. Also, the cuttings and the drill bit are not taken into account. The drill pipe and the annular space are concentric, as depicted in Fig 1. It is considered that the influx takes place at the well bottom and only migrates through the annular space.

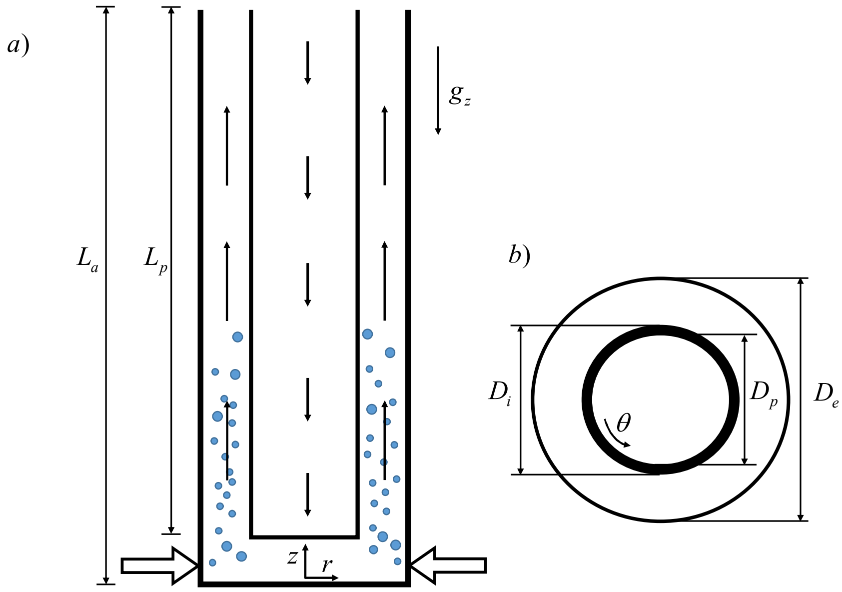

Figure 1. a) Schematic representation of the geometry used and the gas influx and b) Cross sectional of drill pipe and annular space.

The two-phase flow is assumed as homogeneous and one-dimensional, therefore the balance of mass for the mixture can be expressed as (Wylie *et al*., 1993):

$$\frac{\partial \rho_m}{\partial t}+\frac{\partial(\rho_m V)}{\partial z}=0 \tag{1}$$

where t is the time, V mixture velocity, z is the axial direction and ρ_m is the mixture density, which can be written as (Hage and Avest, 1994):

$$\rho_m=\rho_f(1-\alpha)+\rho_g\alpha \tag{2}$$

where ρ_f and ρ_g are, respectively, the drilling fluid and gas densities and α is the gas void fraction, given by:

$$\alpha=\frac{\forall_g}{\forall_g+\forall_f} \tag{3}$$

where $\forall_g$ and $\forall_f$ are the volume of gas and the volume of drilling fluid.

The ideal gas law is only valid for low pressures and high temperatures. Out of these conditions, the behavior of gases deviates significantly from that predicted by the ideal gas law (Çengel and Boles, 2006). Therefore, the compressibility factor Z is employed and trough the gas state equation is possible to write an expression for the gas density:

$$\rho_g = \frac{P_g}{ZRT} \tag{4}$$

where P is the absolute pressure, R is the universal gas constant and T is the gas absolute temperature.

The compressibility factor employed is the one proposed by Yaborough and Hall (1974):

$$Z = \frac{0.06125 P_{red} T_{red}^{-1} \exp\left(-1.2\left(1 - T_{red}^{-1}\right)^2\right)}{Y} \tag{5}$$

where the subscript red refers to the reduced properties. Y is calculated by:

$$\begin{aligned} &-0.06125 P_{red} T_{red}^{-1} \exp\left(-1.2\left(1 - T_{red}^{-1}\right)^2\right) + \frac{Y + Y^2 + Y^3 + Y^4}{\left(1 - Y\right)^3} = (14.67 T_{red}^{-1} - 9.76 T_{red}^{-2} + 4.58 T_{red}^{-3}) Y^2 - \\ &-\left(90.7 T_{red}^{-1} - 242.2 T_{red}^{-2} + 42.4 T_{red}^{-3}\right) Y^{\left(2.18 + 2.82 T_{red}^{-1}\right)} \end{aligned} \tag{6}$$

For an isothermal flow with low void fraction, the pressure-wave speed in the mixture c_m can be related to the bulks modulus for the mixture K_m (Wylie *et al.*, 1993):

$$c_m = \sqrt{\frac{K_m}{\rho_m}} \tag{7}$$

The isothermal compressibility of the mixture β_m can be expressed as (Adepoju, 2006):

$$\beta_m = \frac{1}{\rho_m} \frac{\partial \rho_m}{\partial P} \tag{8}$$

By disregarding the variation of density along the axial direction and combining Eq. (1) with Eq. (8):

$$\frac{\partial P}{\partial t} + \rho_m c_m^2 \frac{\partial V}{\partial z} = 0 \tag{9}$$

For flows with low void fraction, the balance of momentum is (Wylie *et al.*, 1993):

$$\frac{\partial V}{\partial t} + \frac{1}{\rho_m} \frac{\partial P}{\partial z} + \frac{2 f V |V|}{D_h} + g_z = 0 \tag{10}$$

where D_h is the hydraulic diameter, g_z is the acceleration of gravity and f is the Fanning friction factor, which according to Fontenot and Clark (1974) for a Bingham fluid is:

$$f = \frac{16 \zeta}{\psi \,\mathrm{Re}_{z,t}} \tag{11}$$

where ζ is the geometry factor, which is 1 for the drill pipe and approximately 1.5 for narrow annular space, which depends on the internal and external diameters. $\mathrm{Re}_{z,t} = \rho_m V D_h / \mu_m$ is the Reynold number which depends on the time and space, and ψ is the fluid conductance.

The mixture viscosity can be expressed as (Meng *et al.*, 2015):

$$\mu_m = \mu_p \left(1-\alpha\right) + \mu_g \alpha \tag{12}$$

where μ_p is the plastic viscosity of the drilling fluid and μ_g is the gas viscosity.

Melrose et al. (1958) proposed the following correlations for the fluid conductance in a pipe and an annular space, which are, respectively:

$$\psi_p = 1 - \frac{\psi_p}{6} Bi_{z,t} + \frac{1}{3}\left(\frac{\psi_p}{8} Bi_{z,t}\right)^4 \tag{13}$$

$$\psi_a = 1 - \frac{\psi_a}{8} Bi_{z,t} + \frac{1}{2}\left(\frac{\psi_a}{12} Bi_{z,t}\right)^3 \tag{14}$$

where $Bi_{z,t} = \tau_0 D_h / V \mu_p$ is the Bingham number which depends on time and space and τ_0 is the yield stress.

Chaudhry (2013) and Wylie *et al*., (1993) deduced simplified expressions for the speed of sound in a liquid-gas mixture, considering that: i) the mixture is homogeneous, ii) isothermal flow and iii) the pressure inside the bubble is independent of surface tension and vapor pressure. By combining the gas and liquid isothermal compressibilities, an expression for the speed of sound in the mixture can be determined (Galdino, 2016):

$$c_m = \sqrt{\frac{\rho_f c_f^2}{\left[1 + \frac{ZmRT \rho_f c_f^2}{P^2}\right]\left[\rho_f \left(1 - \frac{ZmRT}{P}\right) + m\right]}} \tag{15}$$

where c_f is the pressure-wave speed in the drilling fluid and m is the mass of gas per unit of volume.

The Darcy's law is employed to represent the gas influx into the wellbore (Dake, 1998):

$$q_g = C_r \left(P_r - P_{BH}\right) \tag{16}$$

where q_g is the radial volumetric flow rate of gas, P_p is the pore pressure, P_{BH} is the instantly bottom hole pressure and C_r is a constant with depends on the properties of the reservoir:

$$C_r = \frac{2\pi k_r h_r}{\mu_g \ln\left(r_r / r_{wb}\right)} \tag{17}$$

where k_r is the reservoir permeability, h_r is the reservoir height, r_r is the reservoir radius and r_{wb} is the external radius of the annular space.

3. NUMERICAL MODELING

3.1 Method of Characteristics

The balance equations of mass and momentum constitute a system of hyperbolic partial differential equations, where the unknown variables are the pressure and velocity and the independent variables are the time and space. To solve the system, the method of characteristic is applied. The method consists in making a linear combination between the balance equations and then the hyperbolic partial differential equations are transformed into total differential equations (Wylie *et al*., 1993). The resulting equations are only valid over the characteristic lines (Chaudhry, 2014). Therefore, there is two pairs of equation:

$$C^+ : \begin{cases} +\dfrac{1}{\rho_m c_m}\dfrac{dP}{dt} + \dfrac{dV}{dt} + \dfrac{2fV|V|}{D_h} - g_z = 0 & \text{(a)} \\ \dfrac{dz}{dt} = +c_m & \text{(b)} \end{cases} \tag{18}$$

$$C^{-}: \quad \begin{cases} -\dfrac{1}{\rho_m c_m}\dfrac{dP}{dt} + \dfrac{dV}{dt} + \dfrac{2fV|V|}{D_h} - g_z = 0 & \text{(a)} \\ \dfrac{dz}{dt} = -c_m & \text{(b)} \end{cases} \tag{19}$$

The Eqs. (18)a and (19)a are the characteristic lines whereas the Eqs. (18)b and (19)b are the compatibility equations. As the compatibility equations are only valid over the characteristic lines, the grid employed is the one showed in Fig. 2. This grid is valid when the pressure-wave speed is constant. During the gas influx, most of the well has only the drilling fluid, where the speed of sound is constant. The length of each cell is defined by $\left(L_p + L_a\right)/N$, where N is the number of cells. The time-step is function of the pressure-wave speed, $\Delta t = \Delta z / c_f$.

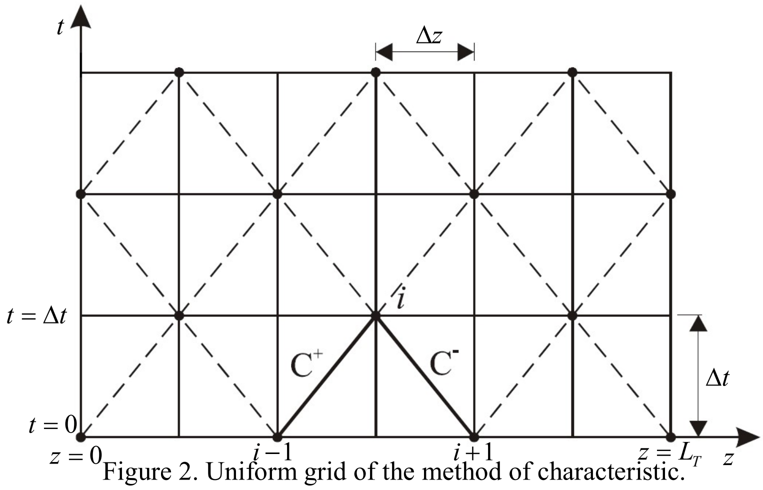

Figure 2. Uniform grid of the method of characteristic.

However, after the gas influx takes place, a region of the well is filled with a gas-drilling fluid mixture. Hence, the pressure-wave speed is not a constant anymore, but function of the amount of gas and the pressure. The characteristic lines that cross the point i do not cross the points $i-1$ and $i+1$, but the points R and S, as depicted in Fig. 3. The pressure and velocity are unknown at the points R and S, but they are only known at the points $i-1$ and $i+1$. Therefore, to maintain the same time-step, a linear interpolation is necessary. The degree of interpolation is $\delta_{R,S} = \overline{c}_m^{\pm} / c_f$, where $\overline{c}_m^{\pm}$ is the average pressure-wave speed along the respective characteristic line.

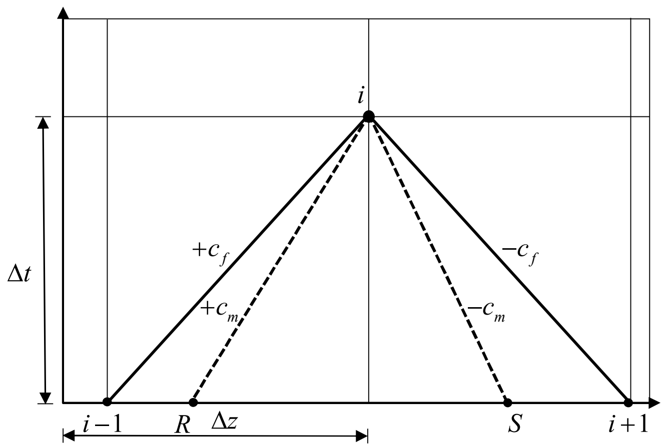

Figure 3. Linear interpolation for pressure-wave speed variable.

By integrating the compatibility equations, Eqs. (18)a and (19)a over their respective characteristic lines, it is possible do determine the pressure and velocity at a future time-step, $n+1$, as function of these properties at the past time-step, n:

$$V_i^{n+1} = \frac{F^+ - F^-}{\overline{\rho}_m^+ \overline{c}_m^+ + \overline{\rho}_m^- \overline{c}_m^- + 16\zeta\Delta z \left(\overline{\mu}_m^+ \delta_R + \overline{\mu}_m^- \delta_S \right) / \psi_i^{n+1} D_h^2} \tag{20}$$

$$P_i^{n+1} = \frac{F^+ + F^- + V_i^{n+1} \left(\overline{\rho}_m^- \overline{c}_m^- - \overline{\rho}_m^+ \overline{c}_m^+ + 16\zeta\Delta z \left(\overline{\mu}_m^- \delta_S - \overline{\mu}_m^+ \delta_R \right) / \psi_i^{n+1} D_h^2 \right)}{2} \tag{21}$$

where $\overline{\rho}_m^\pm$, $\overline{c}_m^\pm$ and $\overline{\mu}_m^\pm$ are the averages of the mixture density, pressure-wave speed and mixture viscosity of the points i and R or S, and the coefficients F^+ and F^- are given by:

$$F^+ = P_R^n + V_R^n \left(\overline{\rho}_m^+ \overline{c}_m^+ - \frac{16\zeta\overline{\mu}_m^+ \Delta z \delta_R}{\psi_R^n D_h^2} \right) - \overline{\rho}_m^+ g_z \Delta z \delta_R \tag{22}$$

$$F^- = P_S^n - V_S^n \left(\overline{\rho}_m^- \overline{c}_m^- - \frac{16\zeta\overline{\mu}_m^- \Delta z \delta_S}{\psi_S^n D_h^2} \right) + \overline{\rho}_m^- g_z \Delta z \delta_S \tag{23}$$

There are two iterative process in the numerical modeling. One process is employed to determine the pressure-wave speed, since it is a function of the pressure. The predictor-corrector technique is applied. The pressure at point i is estimated as the average between the pressures at the points $i-1$ and $i+1$, thus an average pressure-wave speed over the characteristic lines can be calculated. Therefore, a new value for the pressure and velocity are obtained by the Eqs. (20) and (21). The average pressure-wave speed is updated and the process is repeated until the desired degree of accuracy be achieved. The other iterative process it to calculate the fluid conductance, which is a function of the velocity. Again, the first estimative made is that the conductance at point i is the average between the conductances at points $i-1$ and $i+1$. Therefore, it is calculated a velocity by the Eq. (20) and a new conductance is obtained. Both iterative processes have a minimum relative residue and a maximum number of iterations.

3.2 Initial and boundary conditions

As initial condition it is assumed a steady-state situation where the drilling fluid is pumped with a constant flow rate over the whole well, $Q(z, t=0) = Q_{in}$. The transient term in Eq. (10) is null and, since the velocity is known, the pressure field can be calculated directly. At $t = 0$ s, the gas influx at the bottom hole takes place.

At the drill pipe surface, the boundary condition set is a constant flow rate of the drilling fluid being pumped into the drill pipe, $Q(z = L_p, t) = Q_{in}$. As the velocity is known, the pressure can be determined.

At the annular space surface, the boundary condition is the atmosphere pressure, $P(z = L_a, t) = P_{atm}$. Once the pressure is given, the velocity at the annular surface can be calculated.

At the bottom hole, there is the coupling between the drill pipe and the annular space, with the gas influx. At this position, there is four unknowns, the pressure and velocity at the drill pipe, and the pressure and velocity at the annular space. Therefore, to solve the problem is necessary four equations. The first two equations are the compatibility equations from the method of characteristics. The third equation is obtained by a balance of mass at the well bottom. The last equation is the Bernoulli equation. The Bernoulli equation is employed to consider the U-tube effect due to the gas influx. Since the gas has lower density than the drilling fluid, the hydrostatic pressure in the annular space will become smaller than the hydrostatic pressure at the drill pipe. Therefore, there will be a tendency to accelerate the flow caused by the difference of hydrostatic pressure.

4. RESULTS

The purpose of the model is to assess the variation in parameters that are monitored during the well drilling caused by a gas kick. Therefore, the parameters employed in the simulation represent the data found in real drilling operations, which are presented in Tab. 1.

Table 1. Parameters employed in the simulation.

Geometry	Drill pipe length	3000	m
	Annular space length	3000	m
	Drill pipe diameter	0.127	m
	Internal annular diameter	0.1397	m
	External annular diameter	0.216	m
Drilling fluid	Density	1300	kg/m³
	Pressure-wave speed	1000	m/s
	Compressibility	$7.69.10^{-10}$	Pa^{-1}
	Dynamic viscosity	0.1	Pa.s
	Yield stress	7.0	Pa
Pumping	Pump flow rate	0.025	m³/s
Gas influx	Darcy's law constant	$5.46.10^{-10}$	m^4.s/kg
	Initial difference between $P_r - P_{BH}$	0.8	MPa
	Gas constant (methane)	518.3	J/kg.K
	Gas temperature	323	K
	Gas density at reservoir	236.7	kg/m³
Simulation parameters	Length of cell	6	m
	Time-step	6	ms
	Maximum residue 1 (MOC)	0.001	
	Maximum residue 2 (Conductance)	1.10^{-6}	m/s
	Iteration maximum number 1	20	-
	Iteration maximum number 2	100	-
Acceleration of gravity		9.81	m/s²

As said earlier, the initial condition is a steady-state condition with the fluid being pumped with constant flow rate at the drill pipe surface. At $t = 0$ s, the kick takes place at the well bottom and gas starts to migrate into the annular space. Since the gas starts to occupy space and has lower density and viscosity than the drilling fluid, it is necessary less pressure to pump the drilling fluid along the well. Therefore, for a same flow rate, the pump pressure starts to decrease, as can be seen in Fig. 4a, where is showed the pump pressure over time. It is possible to notice a slightly pressure increase just after the kick has started. At the moment the gas enters the well, it compresses the drilling fluid generating a pressure-wave. When the pressure-wave reaches the surface, it increases the pressure. After this, the pressure decreases continuously as the presence of gas in the annular space results the U-tube effect due to the difference of hydrostatic pressure. It is also possible see that, after some time, the drop rate of pressure increases. This behavior is caused by the loss of hydrostatic pressure in the annular space, which increases the gas influx, reducing even more the pressure, feeding the cycle.

The downhole pressure is sometimes measured (Carlsen *et* al., 2013). When it is measured, it can be used to indicate a gas influx. The pressure at the bottom of annular space is showed in Fig 4b. Comparing the decrease rates of pressure in Figs. 4a and 4b, it is possible to observe that the decrease rate of pressure is smaller at well bottom. The pressure decrease at well bottom is caused only by the loss of hydrostatic pressure, whereas at the drill pipe surface is caused by U-tube effect and also because the mixture gas-liquid has smaller viscosity than the drilling fluid.

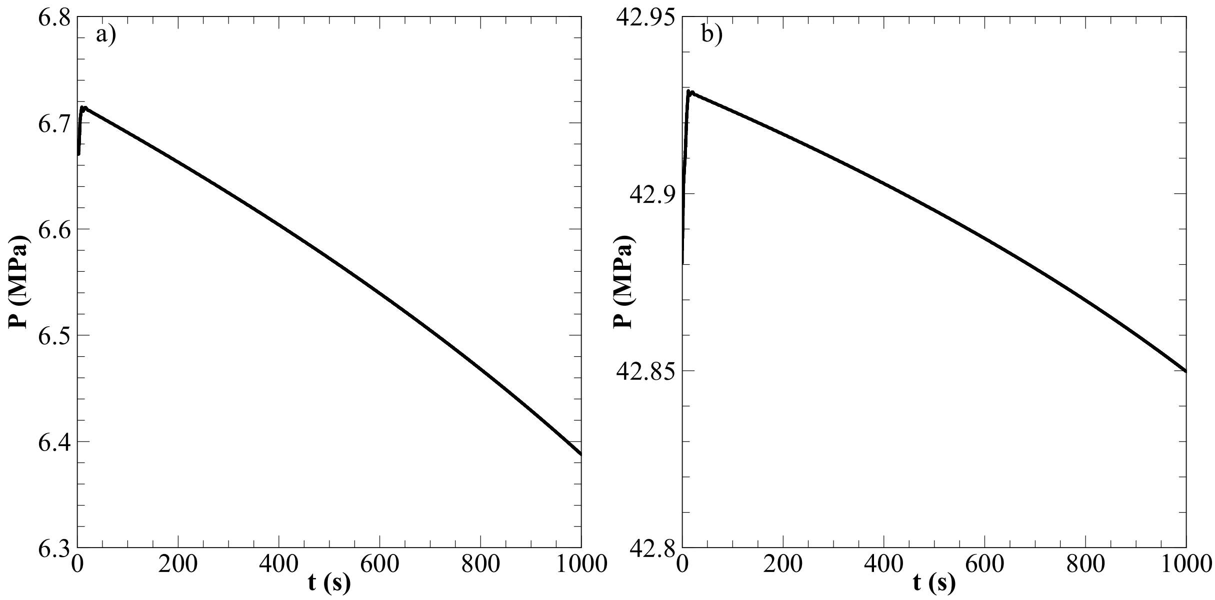

Figure 4. a) Time evolution of pump pressure and b) Time evolution of the bottom hole pressure.

The outlet flow rate is a primary indicator of gas kicks, however it has an inaccurate measurement (Carlsen *et al.*, 2013). Fig. 5 presents the inlet and outlet flow rate over time during the gas kick. As the inlet flow rate is set as a boundary condition, it remains constant over time. In the other hand, the outlet flow rate increases over time. It takes about 3 seconds to the gas influx change the outlet flow rate. After an abrupt increase at the beginning, the outlet flow rate increase slightly over time. This increase is caused by the increase of gas influx over time, as a consequence of the reduction of downhole pressure, as showed in Fig. 4b. However, the changes in the outlet flow rate caused by the kick may not be detected due to the inaccurate measurement.

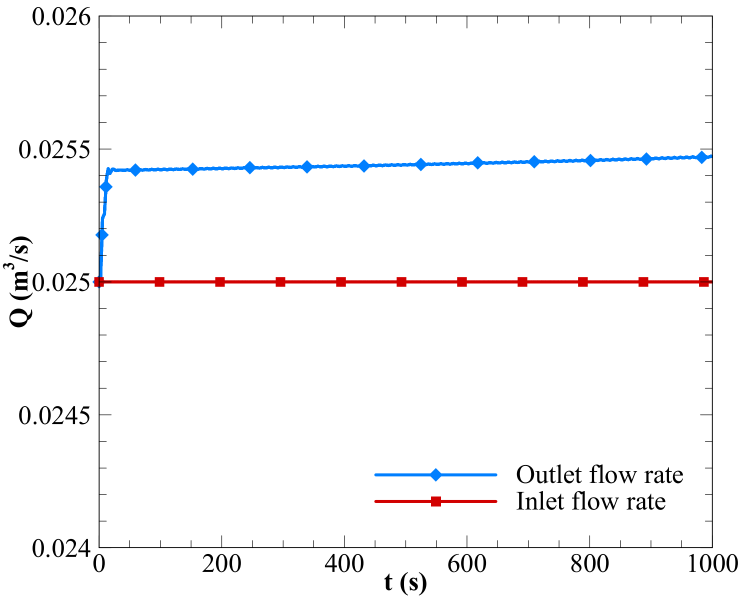

Figure 5. Time evolution of the inlet and outlet flow rates during gas kick.

The pit-gain is the increase of mud volume in the pit-tanks (Carlsen *et al.*, 2013). Due to the big surfaces areas of the tanks, it is needed a high amount of gas to result in a detectable increase in the mud level. Also, the pitch and roll of the rig difficult the measurement. Furthermore, the path from the annular surface to the pit tank takes minutes, since the drilling fluid passes through a cleaning process. Notwithstanding, the pit-gain is one of the main parameters for the kick detection. Fig. 6 presents the level increase of mud drilling over time during gas kick. It was considered that it takes 2 minutes for the drilling fluid go out of the annular space and arrive at the pit tank. Also, 40 m² was set as the surface area and 2 m was the initial level of the mud. After 1000 s, it was gained 0.38 m² of volume, which results in a level increase of only 1 cm.

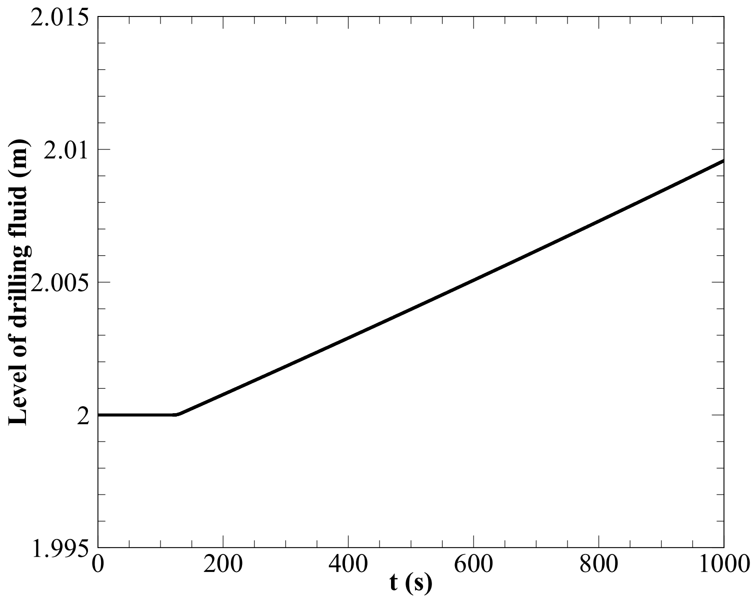

Figure 6. Time evolution of the level of drilling fluid in the pit tanks.

During the well drilling, close to the drill bit is generated micro pulses of pressure, which travel with the speed of sound in the drilling fluid. These pulses transmit information to the surface. As the presence of gas reduce considerably the speed of sound in liquids, an increase in the time response in the telemetry can be a gas kick indicator. Fig. 7 presents the time evolution of the time response of pulses in the annular space and in the drill pipe. As gas only invades the annular space, the time response in the drill pipe remains constant. Whereas the time response in the annular space gradually increases over time. After 1000 s of the kick beginning, the time response in the annular space increased more than 10%. By analyzing the expression for the pressure-wave speed in the mixture, Eq. (15), it is possible to observe that it is directly proportional to the pressure and inversely proportional to the amount of gas. Over time, the length occupied by the gas in the annular space increases, affecting the time response. Also, the gas migrates toward surface, therefore the hydrostatic pressure acting on the gas reduces, reducing then the pressure-wave speed even more.

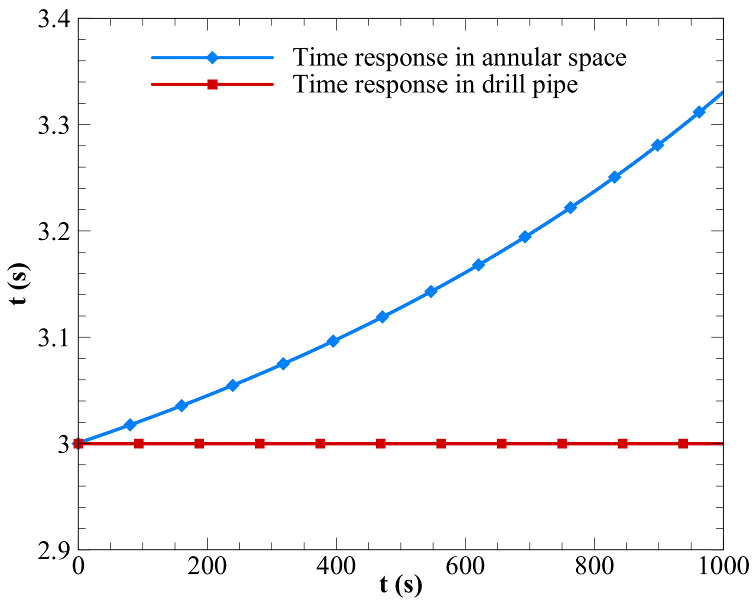

Figure 7. Time evolution of the time response of pulses during gas kick.

5. CONCLUSIONS

The current work presents a mathematical and numerical modeling to represent the transient two-phase flow that occur during gas kicks. The purpose is to analyze the changes in pump and downhole pressures, outlet flow rate, time-response in telemetry and pit-gain caused by the gas influx. The two-phase flow is assumed as homogeneous and the balance equations of mass and momentum are solved by the method of characteristics. Among the parameters analyzed, in percentage rates, the least sensitive parameter to the gas kick was the downhole pressure, which the gas influx only changed about 0.1% during 1000 s. The second least sensitive parameter was the pit-gain, which has a considerable delay to respond to a gas influx and the big surfaces areas of the tanks make difficult the kick detection. The pump pressure and the outlet flow rate responded very quickly to the gas kick. The complicating factor to rely more upon the outlet flow rate is the inaccurate measurement. The most sensitive parameter to the gas kick was the time response of a pulse in the annular space, which has increased more than 10% after 1000 s of the kick beginning.

6. ACKNOWLEDGEMENTS

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