Hindawi Publishing Corporation
Journal of Applied Mathematics
Volume 2014, Article ID 969465, 12 pages
http://dx.doi.org/10.1155/2014/969465

Research Article

A New Method for Predicting the Position of Gas Influx Based on PRP in Drilling Operations

Xiangwei Kong,[1] Yuanhua Lin,[1,2] and Yijie Qiu[1]

[1] *State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China*
[2] *CNPC Key Lab for Tubular Goods Engineering, Southwest Petroleum University, Chengdu, Sichuan 610500, China*

Correspondence should be addressed to Yuanhua Lin; yhlin28@163.com

Received 6 December 2013; Accepted 7 March 2014; Published 16 April 2014

Academic Editor: Jong Hae Kim

Accurately predicting the position of gas influx not only helps to analyze complex formation structure, but also can provide reference for taking effective measure, such as increasing mud density, increasing back pressure and casing packer, to suppress the gas influx. Predicting the accurate position of gas influx has been one of the urgent difficulties for drilling industry. With full consideration of the important factors such as the virtual mass force, viscous shear force, energy exchange, and narrow resistance, a new method for predicting the position of gas influx has been proposed based on pressure response time calculation. The gas equations of state (EOS), small perturbation theory, and the fourth-order Runge-Kutta method (R-K4) are adopted to solve the model. Also, the pressure response time plate (PRP) which presents the corresponding relationship between position of gas influx and wellhead parameters by several pressure wave response curves calculated by computer programming is given. The results showed that the PRP is unique at different well depth and gas influx rate, and the position of gas influx can be accurately determined by PRP with known wellhead parameters and detected response time. Therefore, without the help of downhole tools, the accurate mathematical method for predicting the position of gas influx is completely feasible.

1. Introduction

One of the future trends of petroleum industry is the exploration and development of high pressure, low permeability reservoirs [1]. Drilling-related issues such as excessive mud cost, wellbore ballooning/breathing, kick-detection limitations, difficulty in avoiding gross overbalance conditions, and differentially stuck pipe and resulting well-control issues together contribute to the applying of managed pressure drilling (MPD) technology [2, 3]. Although drilling operations try to avoid the risk of gas influxes in MPD operations, occasionally there are gas influxes for various reasons. Since the subsequent influx of gas displaces drilling mud, it decreased the pressure in the wellbore and makes gas enter even faster [4, 5]. Gas influx occurs whenever the pressure of a gas-bearing formation exceeds the pressure at the bottom of a wellbore [6]. The main reasons for gas influx are this pressure differentia; the pressure differentia is an unexpected form of rise in formation pressure or a decrease in mud hydrostatic pressure. A rise in formation pressure can be due to geological processes that have occurred in the region being drilled. Wells are drilled in regions where oil and gas are trapped, and the same processes that create the hydrocarbons can also produce large pressures. Therefore, it is not uncommon to come across regions of abnormally high formation pressure while drilling. Mud hydrostatic can decrease due to any event that causes the mud column in the hole to drop, such as lost circulation or tripping out while not filling the hole to adequately compensate for the volume of the removed drilling assembly [7]. Surge pressure, low drilling mud density, abnormal formation pressure and so forth all can cause that the formation pressure be higher than annulus pressure during MPD process, and the higher formation pressure can lead to gas influx from formation to annulus. At any operation condition, the negative pressure exists between the annulus and the formation when gas influx occurs. If the gas influx cannot be detected in time and take effective measures, the negative pressure differentia will further increase with the migrate of gas along the annulus from bottomhole to wellhead. It can result in further deterioration of influx which may escalate into a blowout creating severe financial losses, environmental contamination, and potentially loss of human lives. Normally, gas influx occurs in bottomhole or casing shoe. But when drilling in complex formation, gas influx may occur anywhere in the open wellbore. Also, gas influx may occur at any time while wellbore pressure falls below formation pore pressure in a permeable and porous zone containing fluids. For drilling safety reasons, the sooner it can be detected, the better it will be . Accurate determination of gas influx position is more conducive to take effective measure for suppressing gas influx [8, 9].

Since there are more unknowns, predicting of formation parameters and borehole fluid parameters is always difficult in the drilling industry. At present, the predicting methods generally include software base monitoring and hardware techniques with the help of measurements-while-drilling tools. In drilling site, many judgment methods are put into use, such as level monitoring of return drilling mud in drilling fluid pot, DC index method, shale density method, torque gauge method, acoustic time difference method, and pump speed method. DC index method relies on the accurate determination of normal pressure trend line. For lack of reliability of pressure monitoring and drilling parameters before drilling, the DC index method has limitations. Acoustic curve detection of formation pressure based on acoustic time difference principles is used for prediction of the single well drilling area or regional formation pressure and regional formation pressure profile, which is common and effective. Acoustic velocity is relevant to the density of the rock structure, porosity of formation, and buried depth. The basic principle of acoustic time difference method is that the propagation velocity of sound waves is different in gas drilling fluid and drilling fluid. Seismic reflection wave method is widely used in geophysical methods. Seismic wave method to predict the formation pressure is according to seismic wave velocity difference to decide the formation pressure. The basic principle of pump speed method is based on working mud pump. The mud pump can be seen as a surface pressure pulse generator. The pressure pulses generated by piston in pump enter the circulatory system, such as the drill string, downhole, drill bit, the nozzle, and return to the ground along the annulus [10–12]. MWD tool is also an important means for detection of downhole information. In the early 2000s, formation pressure while-drilling tools were introduced. That can obtain formation pressure data, even in highly deviated wells and extended-reach drilling. In earlier research, a numerical solution of the equations that govern unsteady fluid flow is developed by Chen et al. in 2005. The boundary conditions are adjusted for the surface and downhole equipment. The program outputs pressure and flow pulse predictions at any point [13]. In the past many years, this LWD technology has evolved with the addition of downhole fluid sampling and fluid analysis. LWD sampling and testing are now performed in challenging environments that cannot be performed with wire line tools such as horizontal or highly deviated wells [14]. The new generation of LWD and MWD tools was specifically designed by Radzinski and LWD in 2004 for such hostile environments, transmitting real-time directional information, gamma ray, bore and annular pressure, vibration data, resistivity, neutron porosity, and density measurements [15]. Chia quantified a significant improvement to standard MWD surveyed position uncertainty using actual survey data from drilling assemblies used in more than 120 runs in over 35 different wells in 2004. The use of multistation analysis and the subsequent reduction in wellbore position uncertainty can reduce overall surveying and drilling costs for the well, removing the need for correction runs and allowing for penetration of smaller targets than previously possible with standard MWD surveying [16]. Wang demonstrated that the application of MWD is not limited to streamer data but can also be extended to ocean bottom seismic (OBS) data. For OBS data, MWD can remove water-layer-related multiples and receiver ghost in one step [17]. An MWD data transmission system and method were provided for determining and transmitting the environmental properties of the downhole borehole assembly (BHA) to surface data receivers via mud pulse telemetry, EM telemetry, or both mud pulse telemetry and EM telemetry based on one or more determined properties of the downhole environment by Young in 2012 [18]. Construction and a field testing of a prototype that can automatically record data while drilling from caving and influx flow were analyzed in real time. The prototype is used to identify situations in which influx and caving flows are high enough to cause instability of the drilled well in real time. Geraud et al. combined different services, such as the BHA which included a rotary steerable system (RSS), measurement and telemetry service, logging-while-drilling (LWD) magnetic resonance service, multifunction petrophysics platform, formation pressure service, and sonic and seismic services in 2013. Measurements from these services are integrated and used for real-time drilling parameter optimization and formation evaluation [19].

Though some efforts have been made, predicting the position of gas influx still depended on measurement while drilling (MWD). In the past researches, the influencing factors for the position of gas influx are simulated and analyzed with the MWD; however, the variation of gas void at different depth of wellbore is not considered [20–22]. The current researches are limited in their assumption and neglect of the flow pattern translation and interphase forces along the annulus. Up to now, no mathematical method to predict position of gas influx in annulus with variation of gas void, flow pattern, temperature, and BP during MPD operations has been derived. The research in this paper will hopefully solve the present puzzle for predicting the position of gas influx occurring in drilling operations. In this paper, the new method for predicting the position of gas influx is proposed based on acoustic time difference method. So, the determination of pressure wave velocity is the key of this method. Since the 1940s, many experimental and theoretical studies for pressure wave velocity have been performed. Experimental tests are conducted to inspect the contributions of fluctuation and flow characteristics on pressure wave. Pressure wave is still worth continuing an in-depth study today [23–29]. In drilling industry, Wang and Zhang studied the pressure pulsation in mud and set up a model for calculating the amplitude of pressure pulsation when pressure wave transmits in drilling-fluid channel especially drilling hose with different inside diameter [30]. Lin et al. study the wave velocity for the transmission of pressure disturbance in the two-phase drilling fluid in the form of a pressure wave in annulus during MPD operations in 2013 [31].

The purpose of this paper is to describe a new method based on pressure response time plate (PRP) for predicting the position of gas influx in the two-phase flow in annulus during MPD operations. In addition to pressure, temperature, and void fraction in the annulus, the compressibility of the gas phase, the virtual mass force, and the changes of interface in two-phase are also taken into consideration. By introducing the pressure gradient equations in MPD operations, gas-liquid two-fluid model, the gas equations of state (EOS), and small perturbation theory, the method for predicting the position of gas influx in gas and drilling mud in annulus is developed. The method can be used to predict the position of gas influx at different influx rate, applied back pressure, and well depth with a full consideration of drilling mud compressibility and interphase forces.

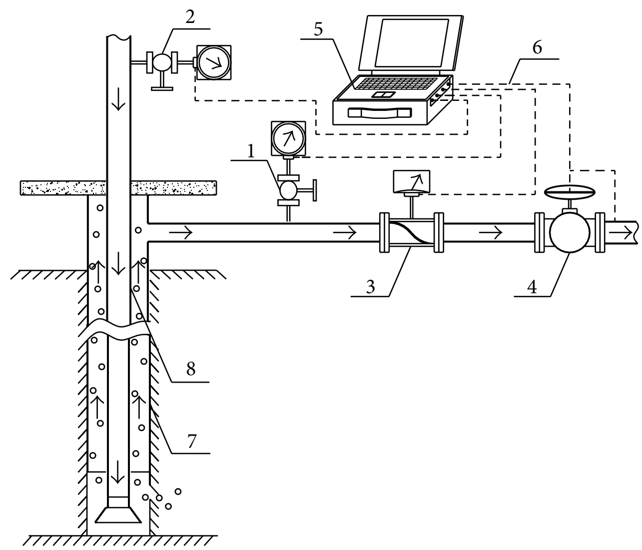


Figure 1: Schematic diagram of pressure response testing ((1) back pressure sensor, (2) stand pipe pressure sensors, (3) gas-liquid flow meter, (4) electronic valve, (5) IPC (industrial personal computer), (6) command lines, (7) casing pipe, and (8) drill pipe).

2. The Mathematical Model

The drilling system described is an enclosed system (Figure 1). The drilling mud is pumped from surface storage, down the drill pipe. Returns from the wellbore annulus travel back through surface processing. The key equipment include pressure sensor, choke, and gas-liquid flow meter as follows.

(i) Pressure sensor: a pressure sensor is used to measure surface back pressure on the wellhead.

(ii) Electronic valve: the MPD choke manifold provides an adjustable choke system which is used to dynamically control the required BHP by means of applying surface BP.

(iii) Gas-liquid flow meter: a gas-liquid flow meter is used to accurately measure the mass flow rate of fluid exiting the annulus. The ability to measure return flow accurately is essential for the applied-back-pressure.

Both gas-drilling mud flow rate measured by gas-liquid flow meter and the back pressure measured by pressure senor are the initial data for pressure response time calculation in annulus.

During MPD operations, if the gas influx occurs in the bottomhole, the pressure wave velocity will be significantly reduced. This is due to the low density and great compressibility of gas. Gas migrates from the position of gas influx to the wellhead along the annulus. Above gas influx position, fluid is composed of gas and two-phase drilling mud. Below gas influx position, fluid is single-phase drilling mud. When gas migrates to the wellhead, the degree of the electronic valve is increased to suppress gas influx occurrence. Adjustment of throttle valve to increase back pressure and suppress gas influx will generating pressure pulse. Pressure pulse propagates from wellhead to bottomhole along the annulus in the form of pressure wave. After arriving at bottomhole, the pressure pulse returns back the wellhead in two different paths, propagating along the drill pipe and propagating along the annulus. The pressure sensor detects the difference of propagation time T_c of the two paths.

Gas influx position accuracy detection relies on the calculation of the pressure response time. Pressure response time is the propagation time of pressure wave from wellhead to bottomhole. The wellbore can be divided into several grids. The algebraic sum of propagation time in every grid is the response time.

Divide the annulus into n discrete grids, and the first grid is at the wellhead ($H_0 = 0$ m, void fraction is ϕ_0, BP is P_0, andwave velocity is c_0). According to the wellhead parameters, the next parameters (ϕ_1, P_1, H_1, c_1) of the grid can be calculated by Runge-Kutta method, followed by the ith grid parameters (ϕ_i, P_i, H_i, c_i) which are obtained. According to the parameters of the ith grid, pressure response time on the corresponding grid can be obtained.

In MPD operations, calculation equation of pressure wave response time based on the wave velocity and well depth is expressed as follows:

$$T(H_i) = \sum_i \frac{H_i}{c_i}, \quad (i \le n), \tag{1}$$

where $T(H_i)$ is the pressure response time on nod i (s); H_i is wellbore length on nod i (m); c_i is wave velocity on nod i (m/s).

If the drilling fluid is composed of gas and two-phase drilling mud in annulus, the wave velocity can be expressed as

$$c_i = c_{gli}(P_i, T_i, \phi_i, w_i, Lg_i), \tag{2}$$

where c_{gli} is wave velocity in gas-drilling mud phase on nod i (m/s); P is pressure (MPa); T is temperature (K); ϕ is gas void fraction; w is angle frequency (Hz); Lg is flow pattern.

If the drilling fluid in drilling pipe is single-phase drilling mud, the wave velocity can be expressed as

$$c_i = c_l, \tag{3}$$

where c_i is wave velocity in single-phase drilling mud (m/s).

Above the gas influx position (nod i), the fluid in annulus is gas and drilling mud two-phase mixture. Pressure response time of pressure pulse in the annulus above the nod i can be expressed as T_1. Consider

$$T_1 = \sum_i \frac{H_i}{c_i (P, T, \phi, w, Lg)}, \quad i \le n. \tag{4}$$

Above the gas influx position (nod i), the fluid in drill pipe is single-phase drilling mud. Pressure response time in drill pipe is expressed as T_2. Consider

$$T_2 = \sum_i \frac{H_i}{c_l}, \quad i \le n. \tag{5}$$

Response time difference ΔT is obtained by calculation.

$$\Delta T = T_1 - T_2. \tag{6}$$

Response time difference T_c is obtained by the detection of two pressure sensor. The precision is defined as δ. Consider

$$\left| T_c - \Delta T \right| < \delta, \tag{7}$$

where T_c is response time difference between the two paths detected by pressure sensor; ΔT is the calculated time difference (s); δ is computational accuracy (s).

The gas influx position can be determined by

$$H = \sum_i H_i, \quad i \le n, \tag{8}$$

where H is the length of wellbore above the gas influx position (m). If the influx occurs at the bottomhole, H amounts to the depth of the well.

Furthermore, each position of gas influx and gas influx rate corresponds to a pressure wave response curve. The PRP presents the corresponding relationship between position of gas influx and wellhead parameters by several pressure wave response curves calculated by the computer programming. With known gas influx rate and pressure wave response time, the position of gas influx can be accurately determined on the basis of the PRP.

3. Governing Equations

In the following part of this section, the calculation equations of pressure wave velocity and flow parameters vary well depths are given.

3.1. Wave Velocity in Gas and Drilling Mud Two-Phase Fluid. The continuous equation for gas phase can be expressed as follows:

$$\frac{\partial}{\partial t}\left(\phi \rho_g\right) + \frac{\partial}{\partial s}\left(\phi \rho_g u_g\right) = 0, \tag{9}$$

where ρ_g is gas density (kg/m^3); u_g is gas flow velocity (m/s).

The continuous equation for drilling mud phase can be expressed as follows:

$$\frac{\partial}{\partial t}\left[\left(1-\phi\right)\rho_l\right] + \frac{\partial}{\partial s}\left[\left(1-\phi\right)\rho_l u_l\right] = 0, \tag{10}$$

where ρ_l is drilling mud density (kg/m^3); u_l is drilling mud flow velocity (m/s).

The momentum conservation equation for gas flow can be expressed as follows:

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\phi \rho_g u_g\right) + \frac{\partial}{\partial s}\left(\phi \rho_g u_g^2\right) = -\frac{\partial}{\partial s}\left(\phi P_g\right) + \frac{\partial}{\partial s} \\ &\quad \times \left[\phi\left(\tau_g^{fr} + \tau_g^{\mathrm{Re}}\right)\right] + M_{gi} - 4\frac{\tau_g}{D}, \end{aligned} \tag{11}$$

where P_g is gas phase pressure (N/m^2); τ_g^{fr} is shear stresses of gas interface (N/m^2); τ_g^{Re} is Reynolds stress of gas interface (N/m^2); M_{gi} is momentum transfer in gas interface (N/m^2); τ_g is shear stresses of gas interface (N/m), and D is annulus effective diameter (m).

The momentum conservation equation for drilling mud flow can be expressed as follows:

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\phi_l \rho_l u_l\right) + \frac{\partial}{\partial s}\left(\phi_l \rho_l u_l^2\right) = -\frac{\partial}{\partial s}\left(\phi_l \rho_l\right) \\ &\quad + \frac{\partial}{\partial s}\left[\phi_l\left(\tau_l^{fr} + \tau_l^{\mathrm{Re}}\right)\right] + M_{li} - 4\frac{\tau_l}{D}, \end{aligned} \tag{12}$$

where P_l, gas phase pressure (N/m^2); τ_l^{fr} is shear stresses of drilling mud interface (N/m^2); τ_l^{Re} is Reynolds stress of drilling mud interface (N/m^3); τ_l is shear stresses of drilling mud along well wall (N/m^2); M_{li} is momentum transfer in drilling mud interface (N/m^2).

Pressure gradient within the annulus consists of weight component, acceleration component, and friction forces component. Based on the theory of two-phase flow, equation used to calculate pressure gradient of drilling fluid can be written as

$$\frac{dP}{dH} = \left(\frac{dP}{dH}\right)_e + \left(\frac{dP}{dL}\right)_f + \left(\frac{dP}{dH}\right)_{\mathrm{ac}}, \tag{13}$$

where $(dP/dH)_e$ is weight component; $(dP/dH)_{\mathrm{ac}}$ is acceleration component; $(dP/dH)_f$ is friction forces component.

The total pressure drop gradient is the sum of pressure drop gradients due to potential energy change, kinetic energy, and frictional loss. By simplifying, (13) used to calculate pressure gradient of gas drilling mud two-phase flow within the wellbore can be written as

$$\frac{dP}{ds} = \rho_m g \sin\theta - \frac{\tau_w \pi D}{A} - \rho_m v_m \frac{dv_m}{ds}, \tag{14}$$

where τ_w is frictional pressure of pipe wall (N/m); ρ_0 is the average density (kg/m^3).

By differential treatment of the two-fluid model, (9)–(12) is converted to vector by aid of *Taylor* formula. The small perturbation theory is also applied to the solution of wave velocity model. According to the solvable condition of the homogenous linear equations that the determinant of the equations is zero, the equation of pressure wave can be expressed in the following form:

$$\begin{vmatrix} \left(\rho_g + c_p\phi\rho_l \frac{u_s^2}{c_g^2}\right) w & \frac{\phi}{c_g^2}\left[1 - c_p\phi_l\right]\frac{u_s^2}{c_l^2} w & -\left[\phi\rho_g k + 2c_p\phi\phi_l\rho_l \frac{u_s}{c_l^2} w\right] & 22c_p\phi\phi_l\rho_l \frac{u_s}{c_l^2} w \\ -\rho_l w & \frac{1-\phi}{c_l^2} w & 0 & -k(1-\phi)\rho_l \\ \rho_l u_r^2 k\left(-\phi c_p + c_r - c_i + c_{m2}\right) & -\phi k\left[1 - \phi_l \frac{c_p u_s^2}{c_l^2} + c_i \frac{u_s^2}{c_l^2}\right] & \begin{array}{c}\phi\left(\rho_g + c_{vm}\rho_l\right) w \\ -i\left(\frac{3}{4}\frac{c_D}{r}\rho_l\phi u_s + \frac{4}{D} f_{gw}\rho_g u_g\right)\end{array} & -c_{vm}\phi\rho_l w + i\left(\frac{3}{4}\frac{c_D}{r}\rho_l\phi u_s\right) \\ \rho_l u_s^2 k\left(\phi_l c_p - 2c_r - c_{m2}\right) & -k\left(\phi_l + c_r\phi \frac{u_s^2}{c_l^2}\right) & -c_{vm}\phi\rho_l w + i\left(\frac{3}{4}\frac{c_D}{r}\rho_l\phi u_s\right) & \begin{array}{c}\rho_l\left[\phi_l + \phi c_{vm}\right] w \\ -i\left(\frac{3}{4}\frac{c_D}{r}\rho_l\phi u_s + \frac{4}{D} f_l\rho_l u_l\right)\end{array} \end{vmatrix} = 0, \tag{15}$$

where $c_i = 0.3$; $c_p = 0.25$; $c_{m2} = 0.1$; $c_r = 0.2$; u_s is slip velocity (m/s); f_l is shear stresses coefficient of drilling mud interface; C_D is the coefficient of drag force; C_{vm} is the coefficient of virtual mass force; f_{gw} is shear stresses coefficient of drilling mud interface; w is angle frequency (Hz); r is average diameter of the bubble (m).

The real value of wave number is determined the pressure wave velocity, and pressure wave velocity in the two-phase flow is defined by

$$c_{gli}\left(P, T, \phi, w, Lg\right) = \frac{\left|w/R^+(k) - w/R^-(k)\right|}{2}, \tag{16}$$

where k is wave number; Re(k) is the real part.

When $\phi = 0$, the c_{li} can be expressed as

$$c_{li} = \frac{1}{\sqrt{\rho_l\left(\left(1/\rho_l\right)\left(d\rho_l/dP\right) + \left(1/A\right)\left(dA/dP\right)\right)}}. \tag{17}$$

3.2. Flow Pattern Analysis. Based on the analysis of flow characteristics in the closed drilling system, it can be safely assumed that the flow pattern in wellbore is either bubble or slug flow. The flow pattern transition criteria for bubbly flow and slug flow given by Orkiszewski et al. are used to judge the flow pattern in the gas-drilling mud two-phase flow [32, 33].

For bubbly flow, the empirical relations can be expressed as follows:

$$\frac{q_g}{q_m} < L_b. \tag{18}$$

For slug flow, the empirical relations can be expressed as follows:

$$\frac{Q_g}{Q_m} > L_b, \qquad N_{gv} < L_s, \tag{19}$$

where Q_g is volume flow rate for gas (m^3/s); Q_m is mixture volumetric flow rate for gas-drilling mud (m^3/s).

The dimensionless number L_b is defined by

$$L_b = 1.071 - \frac{0.7277 v_m^2}{D}, \tag{20}$$

where v_m is mixture flow velocity for gas and drilling mud (m/s).

The dimensionless number L_s is defined by

$$L_s = 50 + 36 N_{gv}\frac{Q_l}{Q_g}, \tag{21}$$

where Q_l is volume flow rate for the drilling mud (m^2/s).

The N_{gv} can be defined by

$$N_{gv} = v_s\left(\frac{\rho_l}{\left(g\sigma_s\right)}\right)^{0.25}, \tag{22}$$

where g is acceleration due to gravity (m^2/s); σ_s is surface tension (N/m^2).

The mixture density of two-phase flow is

$$\rho_m = \phi_l\rho_l + \phi\rho_g, \tag{23}$$

where ρ_m is gas and drilling density (kg/m^3); ϕ is gas void fraction; ϕ_l is drilling mud holdup.

Drilling mud holdup can be expressed as follows:

$$\phi_l = 1 - \phi. \tag{24}$$

3.2.1. Bubble Flow. Gas void fraction for bubble flow is

$$\phi_g = \frac{v_{sg}}{S_g\left(v_{sg} + v_{sl}\right) + v_{gr}}, \tag{25}$$

where v_{sg} is superficial gas velocity (m/s); v_{sl} is superficial drilling mud velocity (m/s).

The value of the distribution factor S_g can be described as

$$S_g = 1.20 + 0.371\left(\frac{D_i}{D_o}\right), \quad (26)$$

where D_i is diameter of the inner pipe (m); D_o is diameter of the outer pipe (m).

Superficial gas velocity v_{gr} can be described as

$$v_{gr} = 1.53\left[\frac{g\sigma_s\left(\rho_l-\rho_g\right)}{\rho_l^2}\right]^{0.25}. \quad (27)$$

3.2.2. Slug Flow. The distribution factor S_g for slug flow can be described as

$$S_g = 1.182 + 0.9\left(\frac{D_i}{D_o}\right). \quad (28)$$

For slug flow, the slip velocity v_{gr} can be calculated as

$$v_{gr} = \left(0.35 + 0.1\frac{D_i}{D_o}\right)\left[\frac{gD_o(\rho_l-\rho_g)}{\rho_l}\right]^{0.5}. \quad (29)$$

3.3. Physical Equations

3.3.1. Equations of State for Drilling Mud. Under $T \leq 130^{\circ}$C, drilling mud density was measured by *Хурwудое* in different temperature, and the empirical formula is expressed as follows [25]:

$$\rho_{PT} = 100\rho_0\left(1 + 4\times 10^{-10}P_l - 4\times 10^{-5}T - 3\times 10^{-6}T^2\right). \quad (30)$$

Here, ρ_0 is density under standard atmospheric pressure (kg/m^3); p_l is pressure of drilling mud (MPa); T is temperature (K).

3.3.2. Equations of State for Gas. State of acidic gas is governed by *Redlich-Kwong* equation:

$$P = \frac{RT}{V-b} - \frac{a}{T^{0.5}V\left(V+b\right)}, \quad (31)$$

where V is gas volume; R is gas constant.

Both a and b parameters can be defined by

$$a = \left(\sum y_i a_i^{0.5}\right)^2, \qquad b = \sum y_i b_i. \quad (32)$$

Here,

$$a_i = \frac{\Omega_a R^2 T_c^{2.5}}{P_c}, \qquad b_i = \frac{\Omega_b R T_c}{P_c}, \quad (33)$$

where $\Omega_a = 0.42748$; $\Omega_b = 0.08664$.

4. Solution of the Model

Obtaining the analytical solution of the mathematical models concerned with flow pattern, void fraction, characteristic parameters, and pressure drop gradient are generally impossible for two-phase flow. In this paper, the Runge-Kutta method (R-K4) is used to discretize the theoretical model.

We can obtain pressure, temperature, gas velocity, drilling mud velocity, and void fraction at different annulus depth by R-K4. The solution of pressure drop gradient equation (14) can be seen as an initial value problem of the ordinary differential equation:

$$\frac{dP}{ds} = F\left(s,P\right), \qquad p\left(s_0\right) = P_0. \quad (34)$$

With the initial value (z_0, p_0) and the function $F(z, p)$, (35) can be obtained as follows:

$$\begin{aligned} k_1 &= F\left(s_0, P_0\right), \\ k_2 &= F\left(s_0 + \frac{h}{2}, P_0 + \frac{h}{2}k_1\right), \\ k_3 &= F\left(s_0 + \frac{h}{2}, P_0 + \frac{h}{2}k_2\right), \\ k_4 &= F\left(s_0 + h, P_0 + hk_3\right), \end{aligned} \quad (35)$$

where h is the step of well depth (m).

The pressure on the nod $i = i + 1$ can be obtained by

$$P_{i+1} = P_i + \Delta P = P_i + \frac{h}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right). \quad (36)$$

In the present work, the mathematical model and pressure wave velocity calculation model are solved by computer programming on *VC++* (Version 2010). The solution procedure for the gas influx position is shown in Figure 2. At initial time, the wellhead back pressure, wellhead temperature, wellbore structure, well depth, and gas and drilling mud properties, and so forth are known. On node i, the pressure wave velocity, pressure gradient, temperature, and the void fraction can be obtained by adopting R-K4. Then, the pressure wave response time T_1, T_2 is calculated based on the calculated parameters, compared with the response time difference detected by sensor. The process is repeated until meeting the accuracy requirement. As the accuracy requirement is met at node i, the gas influx occurs at node i. Finally, the distance from the wellhead H can be obtained.

5. Analysis and Discussion

Both gas and drilling mud flow rate measured by gas-liquid flow meter and the BP measured by pressure senor are the initial data for annulus pressure calculation. The experiment well MF6# used for calculation is a gas well in Sichuan Chengdu Region, Southwest China, and the response time test was conducted on May 23, 2013. The wellbore structure,

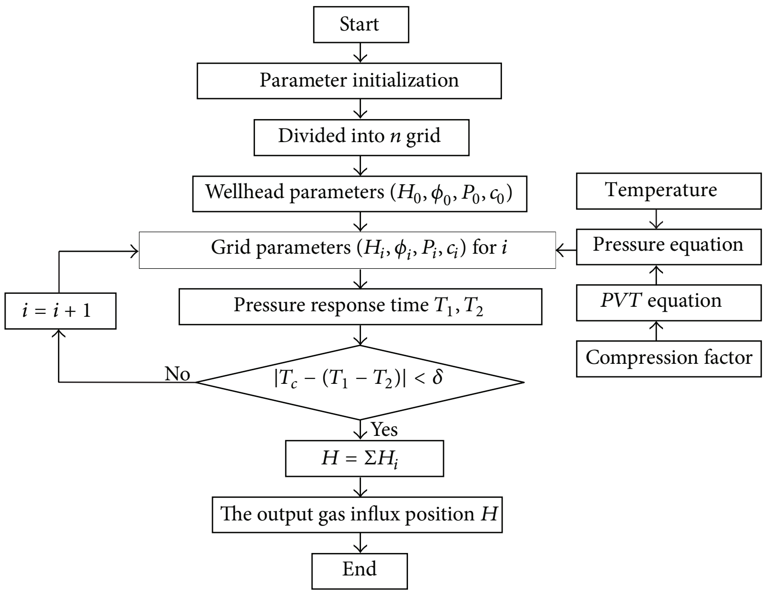


Figure 2: Solution procedure for gas influx position in MPD operations.

Table 1: Basic parameters.

Parameter	Value
The length of drill collar (m)	200
The length of drill pipe (m)	3800
Diameter of bit (m)	0.2159
Outside diameter of drill pipe (m)	0.127
Inside diameter of drill pipe (m)	0.1086
Outside diameter of drill collar (m)	0.1778
Inside diameter of drill collar (m)	0.078
Drill pipe roughness (m)	0.0154
Flow rate for mud pump (m^3/s)	0.037
String elastic modulus (Pa)	2.07×10^{11}
Drilling mud density (kg/m^3)	1460
String Poisson's ratio	0.3
Drilling fluid compressibility (1/kPa)	5.7×10^{-8}
Surface temperature (°C)	25
The ground atmospheric pressure (MPa)	0.101
The wall roughness (m)	0.1

well design parameters (depths and diameters), gas-drilling mud properties (density and viscosity), and operational conditions of calculation well are displayed in Table 1. The length of well is 4000 m, which is divided into 1000 grids. The length of each grid is 10 m in the calculation. Figure 3(a) shows the experimental equipment in MPD field. A dynamic pressure senor is used to measure pressure disturbance time at the wellhead and pressure disturbance return time to verify the pressure response time.

The calculated pressure response time plate is given in Figures 3(b1) and 3(b2). Individually, the two plates present the corresponding relationship between response time and position of gas influx when gas influx occurs or not. Experimental results show that the pressure response time has good consistency with the experimental data. The computer programming can be installed in IPC in real-time in drilling site, and the precision can meet the engineering requirements.

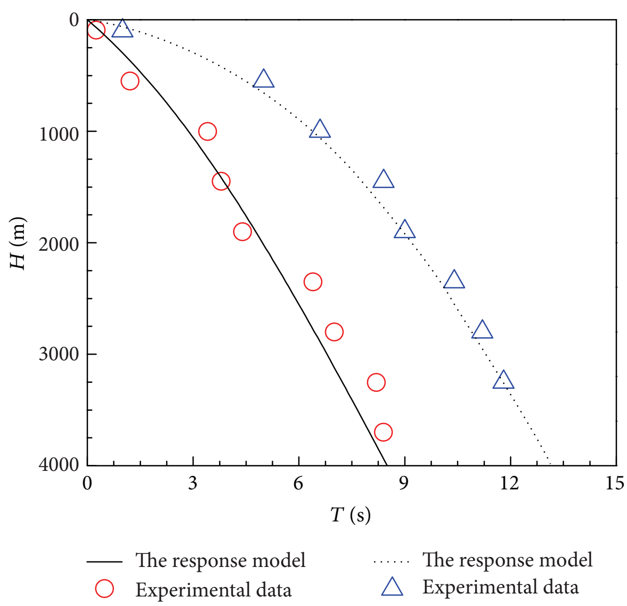
The calculated PRP is unique at different gas influx position and gas influx rate. According to the corresponding principle, the gas influx position can be determined on the basis of the PRP with the known detected response time different when gas influx occurs. Table 2 lists the position of gas influx predicted based on the method in this paper during drilling operations. The key parameters, wave velocity and pressure response time, used for gas influx position predicting are also analyzed in Figures 4–9.

5.1. Effect of BP on PRP. Figures 4 and 5 show the distributions of wave velocity and variations of pressure response time along the flow direction in the annulus when the back pressure at the wellhead is BP = 0.1 MPa, BP = 1.0 MPa, BP = 2.6 MPa, BP = 4.5 MPa, BP = 7.0 MPa, BP = 10.0 MPa, BP = 14.0 MPa, and BP = 19.0 MPa, respectively. It can be seen that the wave velocity significantly decreases along the flow direction in the annulus. Conversely, the pressure response time shows a remarkable increase tendency. This can be explained from the viewpoints of mixture density and compressibility of two-phase fluid and the pressure drop along the flow direction in the wellbore. According to the EOS, if gas invades into the wellbore with a small amount in the bottomhole, the density of the drilling mud has little variation while the compressibility increases obviously, which makes the wave velocity decrease, and the pressure response time shows an increase tendency. Then, the gas migrates from the bottomhole to the wellhead along the annulus with a drop of pressure caused by potential energy change, kinetic energy, and frictional loss, which leads to an increase of pressure

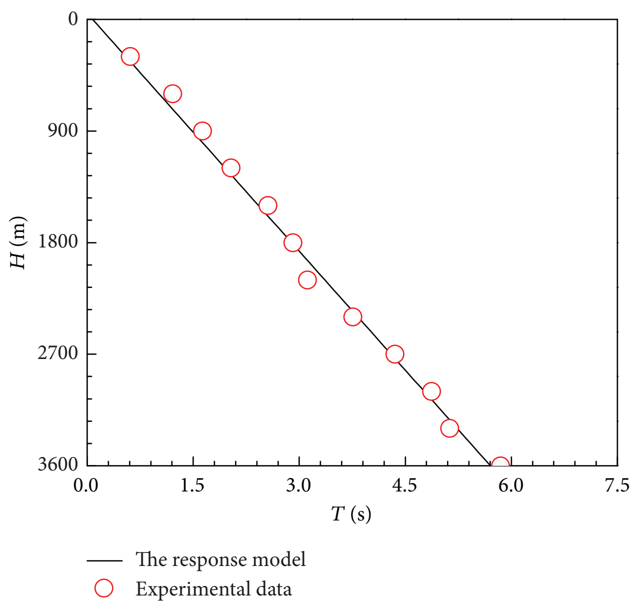
Table 2: Predicted position of gas influx during MPD operations.

	Receive data from IPC			Test result (m)
BP (MPa)	Drilling mud flow (L/s)	Gas flow (L/s)	Time difference T_c (s)	
0.07	38	23.63	10.25	3081
0.11	37	25.12	11.25	3162
0.15	38	15.29	8.75	2925
0.25	45	5.76	7.25	3286
0.27	41	0	0	No gas influx
0.35	37	0	0	No gas influx
0.51	46	0	0	No gas influx
0.61	39	0	0	No gas influx

(a) Experimental equipment in MPD field



(b1) Pressure response time when gas influx occurs



(b2) Pressure response time when gas influx does not occurs

Figure 3: Experimental verification in comparison with field data.

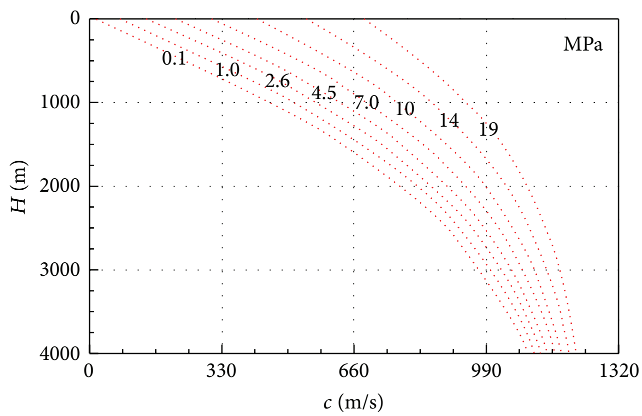


Figure 4: Wave velocity distribution at different BP.

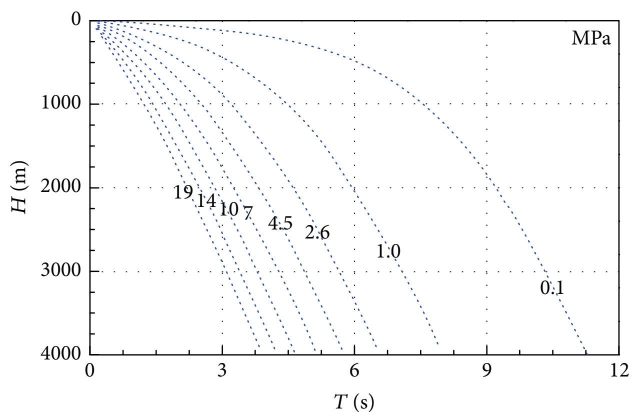


Figure 5: Pressure response time variations at different BP.

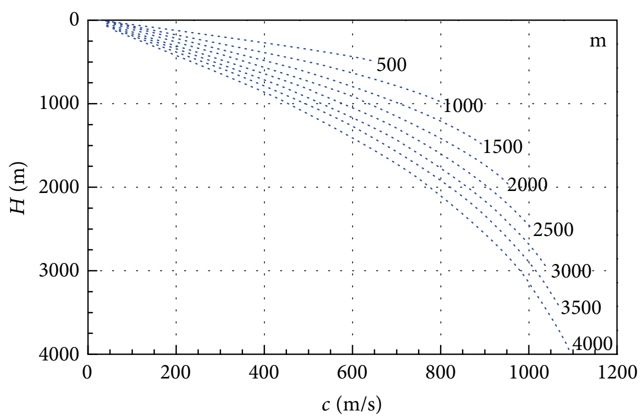


Figure 6: Wave velocity distribution at different well depth.

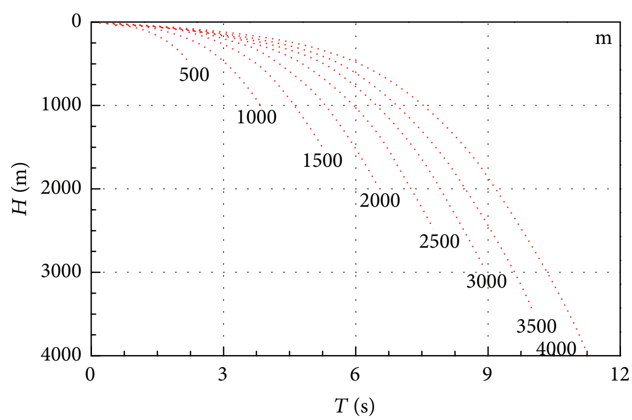


Figure 7: Pressure response time variations at different well depth.

response time. If the wave velocity is increased, resulting in a decrease for pressure responses time along the flow direction.

5.2. Effect of Well Depth on PRP. Figure 6 presents the change of pressure wave velocity in the annulus at different well depth. Figure 7 shows the effect of well depth on pressure response time in gas-drilling mud flow. When the gas influx ($Q_g = 1.28\,\mathrm{m^3/h}$) occurs at different well depth (such as $H = 500\,\mathrm{m}$, $H = 1000\,\mathrm{m}$, $H = 1500\,\mathrm{m}$, $H = 2000\,\mathrm{m}$, $H = 2500\,\mathrm{m}$, $H = 3000\,\mathrm{m}$, $H = 3500\,\mathrm{m}$, and $H = 4000\,\mathrm{m}$), gas invades into the wellbore and migrates from the bottomhole to the wellhead along the flow direction. It can be clearly seen from the curves that the wave velocity and pressure response time are varied in real time due to variation of pressure along

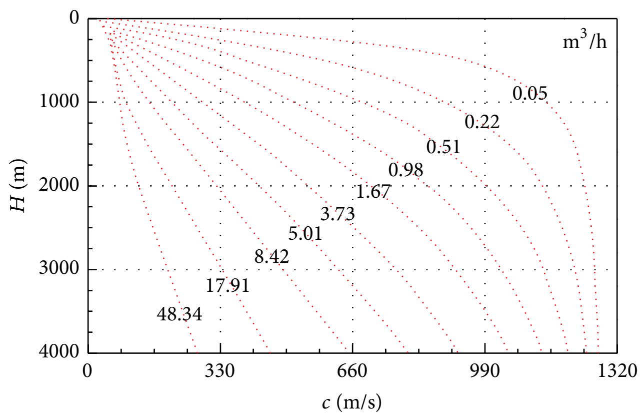


Figure 8: Effect of gas influx rate on the wave velocity.

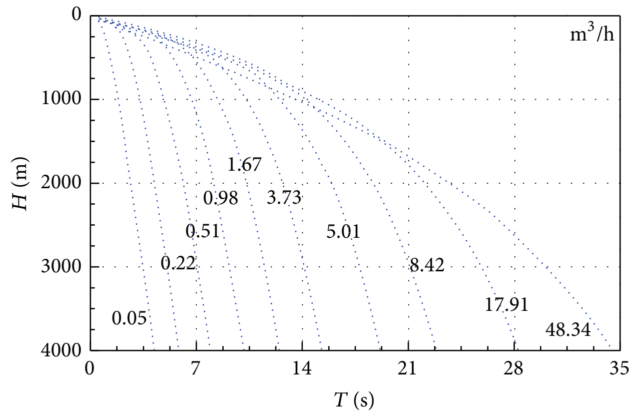


Figure 9: Effect of gas influx rate on the pressure response time.

annulus. With the increase of well depth, both wave velocity and pressure response time are increased. The wave velocity in the two-phase drilling fluid and the distribution of pressure response time at different depth of the annulus will diverge. In conclusion, the wave velocity and pressure response time increase accompanying the increase of the well depth.

5.3. Effect of Gas Influx Rate on PRP. Figures 8 and 9 present the variations of wave velocity and pressure response time along the flow direction in the annulus during MPD operations at different gas influx rate (such as $Q_g = 0.05\,\text{m}^3/\text{h}$, $Q_g = 0.22\,\text{m}^3/\text{h}$, $Q_g = 0.51\,\text{m}^3/\text{h}$, $Q_g = 0.98\,\text{m}^3/\text{h}$, $Q_g = 1.67\,\text{m}^3/\text{h}$, $Q_g = 3.73\,\text{m}^3/\text{h}$, $Q_g = 5.01\,\text{m}^3/\text{h}$, $Q_g = 8.42\,\text{m}^3/\text{h}$, $Q_g = 17.91\,\text{m}^3/\text{h}$, and $Q_g = 48.34\,\text{m}^3/\text{h}$) in bottomhole. When gas influx occurs in the bottomhole, gas invades into the wellbore and migrates from the bottomhole to the wellhead along the flow direction. It is extremely obvious that the wave velocity and pressure response time first change slightly then sharply change in a comparatively smooth value. The compressibility of the gas is high at wellhead, which results in a change of wave velocity and pressure response time. Since the compressible component increases with the increase of gas influx rate, the compressibility of the gas and drilling mud two-phase fluid is improved, so the variations of wave velocity and pressure response time become more prominent. Under the high bottomhole pressure (up to 52 MPa), the change of gas compressibility is low, changing slightly. In conclusion, the pressure response time is sensitive to the wave velocity. Both the wave velocity and pressure response time are dominated by gas influx rate and pressure in the annulus, especially the gas influx rate. Within the range of high gas influx rate, the wave velocity decreases significantly.

6. Conclusions

A new method for predicting the position of gas influx in drilling operations based on PRP has been proposed. The mathematical model is solved by compiled code on *VC++* (Version 2010) language. The main conclusions can be summarized as follows.

(1) In this paper, the pressure response time plate is calculated with full consideration of important factors which has influence on wave velocity. Experimental results show that the calculated pressure response time has good consistency with the experimental data.

(2) When gas influx occurs and migrates along the flow direction in the annulus from the bottomhole to wellhead, the wave velocity first slightly decreases and then sharply decreases. With the gas influx rate decreases or the BP increases, the wave velocity increases and pressure responses time decreases. Pressure response time is sensitive to the wave velocity. Both the wave velocity and pressure response time are dominated by gas influx rate and pressure in the annulus, especially the influx rate.

(3) The calculated PRP is unique at different gas influx position and gas influx rate. According to the corresponding principle, the gas influx position can be determined on the basis of the PRP with the known detected response time when gas influx occurs.

(4) Without the help of downhole tools, an accurate mathematical model to predict the position of gas influx based on PRP is of great importance and is feasible. The computer programming of mathematical model can be installed in the IPC to predict the position of gas influx in real time in drilling site. The new method provides accurate prediction of gas influx position in comparison with the field experiment. The prediction method is not only quickly and accurate, but it also saves drilling nonproductive time (NPT).

Subscripts

BP: Back pressure (MPa)
EOS: Equations of state
IPC: Industrial personal computer
MPD: Managed pressure drilling
MWD: Measurement while drilling
PRP: Pressure response time plate
R-K4: The fourth order explicit Runge-Kutta.

Subscripts of Graph

c: Wave velocity in gas and drilling mud two-phase flow (m/s)
H: Well depth (m)
Q_g: Gas influx rate at the bottomhole (m^3/h)
T: Pressure response time(s).

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

Research work was cofinanced by the National Natural Science Foundation of China (no. 51274170) and Important National Science and Technology Specific Projects (2011ZX05022005-005HZ). Without their support, this work would not have been possible.

References

[1] Y. Bu, F. Li, Z. Wang, and J. Li, "Preliminary study on air injection in annuli to manage pressure during cementing," in *Proceedings of the 2nd SREE Conference on Chemical Engineering (CCE '11)*, pp. 329–334, December 2011.

[2] P. Vieira, F. Torres, R. A. Qamar, G. E. Marin et al., "Down hole pressure uncertainties related to deep wells drilling are safely and precisely ascertained using automated MPD technology," in *Proceedings of the North Africa Technical Conference and Exhibition, Society of Petroleum Engineers*, 2012.

[3] S. Saeed, R. Lovorn, and K. Arne Knudsen, "Automated drilling systems for MPD C-the reality," in *Proceedings of the IADC/SPE Drilling Conference and Exhibition*, 2012.

[4] J. A. Tarvin, I. Walton, P. Wand, and D. B. White, "Analysis of a gas kick taken in a deep well drilled with oil-based mud," in *Proceedings of the SPE Annual Technical Conference and Exhibition*, pp. 255–264, October 1991.

[5] W. Guo, F. Honghai, and L. Gang, "Design and calculation of a MPD model with constant bottom hole pressure," *Petroleum Exploration and Development*, vol. 38, no. 1, pp. 103–108, 2011.

[6] J. Choe and H. Juvkam-Wold, "A modified two-phase well-control model and its computer applications as training and educational tool," *SPE Computer Applications*, vol. 9, no. 1, pp. 14–20, 1997.

[7] W. A. Bacon, "Consideration of Compressibility Effects for Applied-back-pressure Dynamic Well Control Response to a Gas Kick in Managed Pressure Drilling Operations," 2011.

[8] P. Vieira, F. Torres, R. Qamar et al., "Down hole pressure uncertainties related to deep wells drilling are safely and precisely ascertained using automated MPD technology," in *Proceedings of the North Africa Technical Conference and Exhibition*, 2012.

[9] S. Wang, C. Qiang, and K. Bo, "Fluctuating pressure calculation during the progress of trip in managed pressure drilling," *Advanced Materials Research*, vol. 468–471, pp. 1736–1742, 2012.

[10] S. H. I. Yong quan, "Determining the Maximum Depth Method for Complex Formation Pneumatic DTH drilling with the Casing," Geology and Exploration, 4, 2009.

[11] S. J. Chen and J. T. Aumann, "Numerical simulation of MWD pressure pulse transmission," in *Proceedings of the SPE Annual Technical Conference and Exhibition*, 1985.

[12] T. S. Collett, M. W. Lee, M. V. Zyrianova et al., "Gulf of mexico gas hydrate joint industry project leg II logging-while-drilling data acquisition and analysis," *Marine and Petroleum Geology*, vol. 34, no. 1, pp. 41–61, 2012.

[13] H. Chen, R. L. Brown, and J. P. Castagna, "AVO for one- and two-fracture set models," *Geophysics*, vol. 70, no. 2, pp. C1–C5, 2005.

[14] B. Joyce, D. Patterson, J. V. Leggett et al., "Introduction of a new omni-directional acoustic system for improved real-time LWD sonic logging-tool design and field test results," in *Proceedings of the SPWLA 42nd Annual Logging Symposium*, 2001.

[15] P. Radzinski and D. B. LWD, "MWD tools overcoming HP/HT demands," *American Oil and Gas Reporter*, vol. 47, no. 7, pp. 71–74, 2004.

[16] C. R. Chia and B. C. De Lima, "MWD survey accuracy improvements using multistation analysis," in *Proceedings of the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*, pp. 143–150, September 2004.

[17] H. Wang, S. B. M. Beck, G. H. Priestman, and R. F. Boucher, "Fluidic pressure pulse transmitting flowmeter," *Chemical Engineering Research and Design*, vol. 75, no. 4, pp. 381–391, 1997.

[18] A. R. Young, MWD data transmission: U.S. Patent 8, no. 509, pp. 2–21, 2012.

[19] M. Geraud, I. Butt, N. Evans et al., "New generation PDC bits set new benchmarks in carbonate drilling, resulting in significant performance improvements and cost savings for the operator," in *Proceedings of the SPE Middle East Unconventional Gas Conference & Exhibition*, 2013.

[20] V. D. Better, "Well control through safe drilling margin identification, influx analysis and direct measurement method for deepwater," in *Proceedings of the Offshore Technology Conference*, vol. 2013, 2013.

[21] J.-W. Park, D. A. Drew, and R. T. Lahey Jr., "The analysis of void wave propagation in adiabatic monodispersed bubbly two-phase flows using an ensemble-averaged two-fluid model," *International Journal of Multiphase Flow*, vol. 24, no. 7, pp. 1205–1244, 1999.

[22] J. Xu and T. Chen, "Acoustic wave prediction in flowing steam-water two-phase mixture," *International Journal of Heat and Mass Transfer*, vol. 43, no. 7, pp. 1079–1088, 2000.

[23] F. Huang, M. Takahashi, and L. Guo, "Pressure wave propagation in air-water bubbly and slug flow," *Progress in Nuclear Energy*, vol. 47, no. 1–4, pp. 648–655, 2005.

[24] B. Bai, L. Guo, and X. Chen, "Pressure fluctuation for air-water two-phase flow," *Journal of Hydrodynamics*, vol. 18, no. 4, pp. 476–482, 2003.

[25] I. Zubizarreta, "Pore pressure evolution, core damage and tripping out Schedulesf: a computational fluid dynamics approach,"

in *Proceedings of the SPE/IADC Drilling Conference and Exhibition*, pp. 5–7, Amsterdam, The Netherlands, March 2013.

[26] C. H. Whitson, "Cyclic shut-in eliminates liquid-loading in gas wells," in *Proceedings of the SPE/EAGE European Unconventional Resources Conference and Exhibition*, pp. 20–22, Vienna, Austria, March 2012.

[27] G. M. de Oliveira, A. Teixeira Franco, C. O. R. Negrao, A. Leibsonhn Martins, and R. A. Silva, "Modeling and validation of pressure propagation in drilling fluids pumped into a closed well," *Journal of Petroleum Science and Engineering*, vol. 103, pp. 61–71, 2012.

[28] Y. Sato and H. Kanki, "Formulas for compression wave and oscillating flow in circular pipe," *Applied Acoustics*, vol. 69, no. 1, pp. 1–11, 2008.

[29] H. Li, Y. Meng, G. Li et al., "Propagation of measurement-while-drilling mud pulse during high temperature deep well drilling operations," *Mathematical Problems in Engineering*, vol. 2013, Article ID 243670, 12 pages, 2013.

[30] X. Wang and J. Zhang, "The research of pressure wave Pulsation in mud pulse transmitting," *Journal of Chongqing University of Science and Technology*, vol. 14, no. 2, pp. 55–58, 2012.

[31] Y. Lin, X. Kong, Y. Qiu et al., "Calculation analysis of pressure wave velocity in gas and drilling mud two-phase fluid in annulus during drilling operations," *Mathematical Problems in Engineering*, vol. 2013, Article ID 318912, 17 pages, 2013.

[32] J. Orkiszewski, "Predicting two-phase pressure drops in vertical pipe," *Journal of Petroleum Technology*, vol. 19, no. 6, pp. 829–838, 1967.

[33] X. Kong, Y. Lin, Y. Qiu et al., "A new model for predicting dynamic surge pressure in gas and drilling mud two-phase flow during tripping operations," *Mathematical Problems in Engineering*, vol. 2014, Article ID 916798, 16 pages, 2014.