DOI 10.1007/s12182-013-0302-5

New development of theories in gas drilling

Guo Boyun* **and Gao Deli****

China University of Petroleum, Beijing 102249, China

© China University of Petroleum (Beijing) and Springer-Verlag Berlin Heidelberg 2013

Abstract: Theories established from engineering fundamentals have been of great value in supporting the design and execution of drilling operations in gas drilling where gas is used as a drilling fluid. This work presents an overview of new theories developed in recent years for special gas drilling operations including horizontal wells. These new theories are found in the areas of gas-mixture flow hydraulics in deviated and horizontal boreholes, hole cleaning of solids accumulation, hole cleaning of formation water, flow diverging for washout control, bit orifice optimization, and depression of formation water influx. This paper provides drilling engineers with updated mathematical models and methods for optimizing design to improve gas drilling performance.

Key words: Air drilling, gas drilling, nitrogen drilling, design optimization, theory development

1 Introduction

Oil and natural gas wells were drilled utilizing portable air compressors as early as the 1920s (Singer, 1958). Popular use of air as a drilling fluid began in the early 1950s (Martin, 1952). The technology became mature in the late 1950s. The types of fluids used in gas drilling have evolved from air, through natural gas, to nitrogen gas. Many operators relied on the readily available air or pipeline gas for their gas drilling requirements in gas drilling operations prior to the 1980s. Both of these techniques of gas drilling are inherently expensive and dangerous. In an effort to lower drilling cost and improve operational safety on gas-drilled directional wells, Meridian Oil assisted the first time in the development of a nitrogen drilling system (Allan, 1994). The nitrogen drilling system provided a safe and economical means of gas drilling in hydrocarbon producing formations. Air was first used to drill Devonian shale gas formations up to 72 degrees of inclination angle in the late 1980s. Since then the types of wells drilled with gas have been expanded from vertical wells, through directional wells, to horizontal wells in various types of formation rocks (Yost et al, 1990). From the very beginning of gas drilling practice, theories established from engineering fundamentals have been of great value in supporting the design and execution of gas drilling operations. Updated theories have been documented several times in the past, including GRI (1997), Lyons et al (2001), and Lyons et al (2009). However, these documents do not reflect the theoretical advances developed in the past 5 years for gas-drilling horizontal wells under complicated geological conditions. This work is aimed to help fill this gap.

2 Evolution of theories

This section outlines the evolution and development of theories used in gas drilling. These theories are found in the areas of multi-phase flow hydraulics in deviated and horizontal boreholes, hole cleaning of solids accumulation, hole cleaning of formation water, flow diverging for washout control, bit orifice optimization, and depression of formation water. These theories provide drilling engineers useful tools for optimizing their gas drilling design. Illustrations in this section are provided only for demonstrations of typical cases and are not explained in detail due to limited space. More detailed information is available from the authors upon request.

2.1 Multiphase flow hydraulics in horizontal wells

The major component of fluid in gas drilling is the gas phase, which can be air, natural gas, carbon dioxide, or nitrogen. Other components include drill cuttings, injected (misting) water, and fluid (water or oil) from rock formations. Angel (1957) was the first investigator who developed a gas-solid 2-phase flow model to simulate gas drilling hydraulics. Guo et al (1994) were the pioneering researchers who extended Angel's analytical model of gas-solid 2-phase flow model from vertical wells to deviated and horizontal wells. They considered volumes and weights of the injected gas and drill cuttings. Guo and Ghalambor (2002) modified Guo et al.'s (1994) analytical model for gas-solid 2-phase flow to form an analytical model for gas-water-solid 3-phase flow. This model considers volumes and weights of the injected gas, injected water, and drill cuttings. Guo and Liu (2011) made Guo and Ghalambor's model more general to a 4-phase flow. It considers the volumes and weights of the injected gas, injected water, produced fluid (water or oil) and drill cuttings. This analytical model is summarized as follows.

---

*Corresponding author. email: guo.boyun@gmail.com

**Corresponding author. email: gaodeli@cast.org.cn

Received July 3, 2013

$$P_b = \sqrt{\left(P_t^2 + \frac{ab}{(a-G)\cos(I_s)}T_s^2\right)\left(\frac{T_s + G\cos(I_s)S}{T_s}\right)^{\frac{2a}{G}} - \frac{ab}{(a-G)\cos(I_s)}[T_s + G\cos(I_s)S]^2} \tag{1}$$

with

$$a = \frac{S_g Q_{g0} + \frac{\pi}{4} d_b^2 S_s R_p + S_f Q_f + S_w Q_w}{Q_{g0}} \tag{2}$$

$$b = \pm \frac{f Q_{g0}^2}{g A^2 d_H} \tag{3}$$

("+" for upward flow; "–" for downward flow)

where

P_b = pressure at the bottom of the annulus section, Pa
P_t = pressure at the top of the annulus section, Pa
T_s = temperature at the top of the annulus section, °K
G = geothermal gradient, °C/m
I_s = inclination angle, degree
S = length of the annulus section, m
Q_{g0} = volumetric flow rate of injected gas, m^3/s
S_g = specific gravity of injected gas, for air $S_g = 1$
d_b = bit diameter, m
S_s = solid specific gravity, for fresh water $S_s = 1$
R_p = rate of penetration (ROP), m/s
S_w = specific gravity of injected water, for fresh water $S_w = 1$
Q_w = water injection rate, m^3/s
Q_f = formation fluid influx rate, m^3/s
S_f = formation fluid specific gravity, for fresh water $S_f = 1$
f = friction factor, dimensionless
g = gravitational acceleration, m/s^2
A = cross-sectional area of flow path, m^2
d_H = hydraulic diameter of the flow path, m

Eq. (1) is not valid for horizontal boreholes because the term $\cos(I_s)$ in the denominator is zero when the inclination angle is 90 degrees. Guo and Liu (2011) showed the following equation for horizontal flow:

$$P_b = \sqrt{P_t^2 + 2abT_s S} \tag{4}$$

Eq. (3) can be used piecewise with segments of different inclination angles to simulate 4-phase flow in a curved section. If the angle-building section has a constant radius of curvature R, there is no need to divide the curve section into a series of slant-hole segments with different inclination angles. Guo and Liu (2011) presented the following solution to gas pressure at the bottom of an arc section:

$$P_b = \sqrt{P_t^2 + 2abRT_{av} I \exp\left[\frac{2aR\sin(I)}{T_{av}}\right]} \tag{5}$$

where

T_{av} = average temperature in the arc section, °K
I = inclination angle at the bottom of the arc section, radian
R = radius of curvature, m

2.2 Hole cleaning of solids accumulation

An adequate gas injection rate is required for lifting and removing drill cuttings to prevent pipe sticking problem in drilling operations. Several criteria and methods for determining the minimum gas volume requirement have been used in the gas drilling industry for hole cleaning of solids accumulation. They fall into two categories: 1) the minimum velocity criterion, and 2) the minimum kinetic energy criterion. The minimum velocity criterion considers the interactions between solid particles, fluids, and the boundary of the flow domain (borehole wall). It uses the concept of terminal velocity to determine the minimum required gas velocity at the deepest large annulus. The terminal velocity of a solid particle is influenced by many factors, including size, shape, and density of the particle; density and viscosity of the fluid and flow regime. Among many mathematical models proposed to account for the effects of these factors, Gray's (1958) model has been widely accepted for small-size hole drilling because it considers particle-wall interaction. Field application of the minimum velocity criterion has been hindered by its requirement of many parameter values that are normally not known at the design stage of gas drilling operations (Guo and Liu, 2011).

The minimum kinetic energy criterion was based on Angel's (1957) pioneering work. The mixture of gas and solid is treated as one homogeneous phase with mixed density and velocity, i.e., interactions between particles and fluids are not considered. Angel's criterion for the minimum volume requirement is based on the experience gained from quarry drilling with air. The minimum annular velocity to effectively remove solid particles from the borehole is usually assumed to be 15 m/s, or 50 ft/sec (ft/s), under atmospheric conditions. This velocity was believed to be high enough to remove dust-like particles in air drilling. Although large cuttings not removed from the vicinity of the bit by the circulating air are reground by the bit teeth, it would be uneconomical to lift large cuttings without first trying to control their initial size at the bit. McCray and Cole (1959) modified Angel's model to allow simulation of cuttings slip velocity with a constant-percentage. Schoeppel and Spare (1967) reported that the gas flow rate values obtained from Angel's method were at least 25% below the actual requirements in the field. This motivated numerous investigators to develop more accurate models to determine the minimum required gas injection rate for gas drilling. These models include those presented by Capes and Nakamura (1973), Sharma and Crowe (1977), Ikoku et al (1980), Machado and Ikoku (1982), Mitchell (1983), Puon and Ameri (1984), Sharma and Chowdry (1984), Wolcott and Sharma (1986), Adewumi and Tian

(1989), and Tian and Adewumi (1991). Guo et al (1994) believed that Angel's method gives values lower than field requirements because Weymouth's friction derived for flow in smooth pipes, was used in Angel's calculations for flow in rough wellbores. However, this wall roughness effect does not explain the discrepancies observed in drilling situations where the cased-hole is a major borehole section. Li et al (2012) found that the size of drill cuttings collected at surface decreases as wellbore deepens. They attributed this effect partially to the grinding effect of gas flow. Recently Li et al (2013) presented a new analytical model considering the gas energy spent on grinding drill cuttings in the annular space. They proposed the following equation to modify Angel's model:

$$\frac{1}{2}\rho_g v_g^2 = \frac{1}{2}\rho_{g0}\left(v_{g0}\sqrt{1+n}\right)^2 \tag{6}$$

with

$$n = \frac{W_g}{\frac{1}{2}\rho_{g0}v_{g0}^2} \tag{7}$$

$$W_g = \frac{100 f_g D_h^2 W_i \rho_s h_{ROP}}{Q_{g0}}\left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \tag{8}$$

where

ρ_g = gas density at bottom hole condition, kg/m^3
v_g = gas velocity at bottom hole condition, m/s
ρ_{g0} = gas density at standard condition, ρ_{g0}= 1.22 kg/m^3
v_{g0} = Angel's gas velocity at standard condition for hole cleaning, v_{g0}= 15 m/s
f_g = fraction of grinding energy contributed by the flowing gas, dimensionless
D_h = hole diameter, m
W_g = the energy spent on grinding cuttings by the gas stream, J/m^3
W_i = fragmentation energy (6,300 W·h/t for clay and 12,740 W·h/t for limestone)
ρ_s = density of solid particle, kg/m^3
h_{ROP} = rate of penetration, m/s
d = final diameter, m
D = initial diameter, m
Q_{g0} = the minimum required gas volumetric flow rate at standard condition, m^3/s

Because ρ_g and v_g in Eq. (6) are gas flow rate-dependent through bottom hole pressure, this equation has to be combined with Eq. (1) to solve for Q_{g0} numerically.

2.3 Hole cleaning of formation water

Liquids (water and/or oil) from wet formations accumulate at the bottom hole when the air/gas injection rate is not high enough to carry them to the surface. Accumulation of the liquids increases the bottom hole pressure, which compresses gas and reduces gas velocity, resulting in reduced carrying capacity of the gas and, in turn, causing solid and more liquid accumulation at the bottom hole. This cycle will create drilling complications such as mud ringing and pipe sticking. Adding foamers (surfactants) to the gas stream can ease this problem to a certain extent. If the liquid production rate is significantly high, additional gas injection capacity is required, or the air/gas drilling needs to be converted to foam drilling. Converting to foam drilling will result in much lower rate of penetration, while waiting for compressors of higher capacity will also reduce the overall drilling performance due to added non-rotating time. A guideline is highly desirable for drilling engineers who are making decisions on whether or not to convert to foam drilling.

A traditional practice of considering the effect of formation fluid influx on hole cleaning is to use the effective rate of penetration obtained using the equivalent rate of penetration of the influx rate (GRI, 1997; Guo and Ghalambor, 2002). Guo et al (2008) conducted a comprehensive study of liquid carrying capacity of gases. They developed a systematic method for predicting the gas volumes necessary to remove formation fluids at various influx rates. Starting from Turner et al.'s (1969) theory of liquid loading in gas production wells, Guo et al (2008) used the minimum kinetic energy criterion to establish the following theory:

$$E_{km} = 281\sqrt{\sigma\rho_L} \tag{9}$$

where

E_{km} = the minimum kinetic energy required to carry up liquid by flowing gas, J/m
σ = interfacial tension between liquid and gas phases, N/m
ρ_L = density of liquid, kg/m^3

The typical values for water-gas interfacial tension and water density are 0.06 N/m and 1,040 kg/m^3, respectively. Eq. (9) yields the minimum kinetic energy value of 1,850 J/m^3. Since this kinetic energy value is greater than the kinetic energy value of 1,540 J/m^3 required for drill cutting removal, this theory explains why hole-cleaning is still a problem even though the gas flow rate is high enough to remove cuttings. The typical values for oil-gas interfacial tension and oil density are 0.020 N/m and 720 kg/m^3, respectively. Eq. (6) gives the minimum kinetic energy value of 1,070 J/m^3 (<1,540 J/m^3). This number implies that the required minimum gas kinetic energy in oil-influx wells is approximately half of that in water-influx wells, meaning that it is easier to clean holes that have oil influx than holes that have water influx. This explains why oil influx is not a significant problem in air/gas drilling.

The first solution for water removal is to increase the gas injection rate to reach the minimum kinetic energy required to lift the water. The kinetic energy per unit volume of gas can be expressed as:

$$E_k = \frac{\rho_g v_g^2}{2} \tag{10}$$

where

E_k = kinetic energy of gas, J/m^3
ρ_g = density of gas, kg/m^3
v_g = gas velocity, m/s

In order to evaluate the gas kinetic energy E_k in Eq. (10) at a given gas flow rate and compare it with the minimum required kinetic energy E_{km} in Eq. (9), the values of gas density ρ_g and gas velocity v_g need to be obtained from ideal gas law, resulting in

$$E_k = \frac{S_g T Q_{g0}^2}{A^2 p} \tag{11}$$

The gas pressure p depends on the hole configuration and gas injection rate as shown in Eq. (1). Combining Eqs. (9) and (11) allows for determination of the minimum gas injection rate required for water removal.

2.4 Flow diverging for washout control

The problem of wellbore washout is frequently encountered in gas drilling. It may be attributed to several factors. One of them is erosion by high-velocity of gas in the narrow annular space outside the drill collar. The best solution to the erosion problem is the partial release of gas to the annular space above the drill collar before it reaches the bit. This fluid divergence technique has been used in aerated drilling to reduce hole washout (Guo et al, 1996). It involves installation of multiple side-jets in the drill string to bypass fluids in the cased hole section. To protect borehole wall, installations of side-jets are not used in the open-hole section because the jets have a radial component that causes severe borehole erosion. Using this technique cannot solve the high-flow rate-induced problems in gas drilling operations because an adequate gas flow rate is required in the annulus at the shoulder of the drill collar, not in the cased-hole section. Use of a new flow-diverting joint (FDJ) was presented by Guo et al (2011) to solve this problem in gas drilling. Fig. 1 illustrates a sketch of the new type of FDJ. It is manufactured with multiple chambers for inserting nozzles of different sizes. These nozzles are exchangeable to obtain a desirable total flow. They are made of hard materials for erosion-resistance. The unique characteristic of the FDJ is that the nozzles are oriented in the axial direction so that the gas flow at the outlet of nozzles does not cause borehole washout.

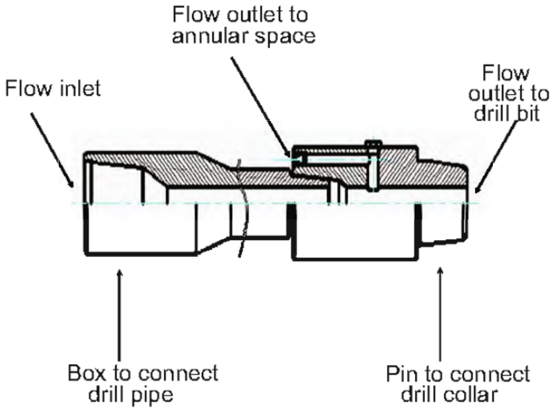

Fig. 1 A sketch of a new type of flow-diverting joint (FDJ)

Fig. 2 shows a flow diagram in the gas drilling system with an FDJ installation at the drill collar shoulder. The total gas injection rate in the drill pipe is divided into two streams, one toward the bottom hole through the drill bit and the other toward the drill pipe-open hole annulus through the nozzles of the FDJ. The optimal area of FDJ nozzles can be designed so that the diverted flow of gas through the FDJ nozzles will reduce the gas flow rate in the drill collar-open hole annulus to a value just enough for hole cleaning. The theory of flow diverging and procedure for designing FDJ nozzles are described by Guo et al (2011). The equation for designing the total FDJ nozzle area is:

$$A_n = \frac{Q_{g0} - Q_{g0c}}{237 P_{up} \sqrt{\frac{k}{(k-1) S_g T_{up}} \left[\left(\frac{P_{dn}}{P_{up}} \right)^{\frac{2}{k}} - \left(\frac{P_{dn}}{P_{up}} \right)^{\frac{k+1}{k}} \right]}} \tag{12}$$

where

A_n = total FDJ nozzle area, m^2
Q_{g0} = total gas injection rate, m^3/s
Q_{g0c} = gas flow rate for achieving a gas energy of 1,850 J/m^3 in the drill collar-open hole annulus, m^3/s
P_{up} = nozzle upstream pressure, Pa
P_{dn} = nozzle downstream pressure, Pa
k = specific heat ratio of gas, 1.4 for air and nitrogen, 1.28 for natural gas
S_g = gas specific gravity, for air S_g=1
T_{up} = nozzle upstream temperature, °K

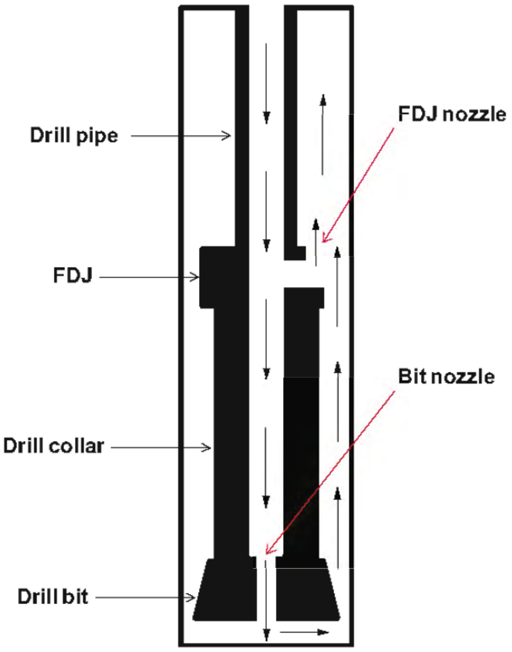

Fig. 2 Flow diagram in the gas drilling system with an FDJ installation

The effect of annulus configuration on the required FDJ nozzle area was investigated using an annulus area ratio (AAR) and nozzle area ratio (NAR) defined as:

$$AAR = \frac{A_{pa}}{A_{ca}} \tag{13}$$

and

$$NAR = \frac{A_{FDJ}}{A_{Bit}} \tag{14}$$

where

A_{pa} = cross-sectional area of drill pipe-open hole annulus, m^2

A_{ca} = cross-sectional area of drill collar-open hole annulus, m^2

A_{FDJ} = total cross-sectional area of FDJ nozzles, m^2

A_{Bit} = total cross-sectional area of bit nozzles, m^2

Fig. 3 shows that the NAR is directly proportional to AAR for a given annular geometry. Fig. 4 demonstrates that the diverging flow to total flow rate ratio is not sensitive to the deepening of the borehole, meaning that there is no need to change FDJ nozzles as drilling progresses as long as the annular-FDJ area ratio remains the same.

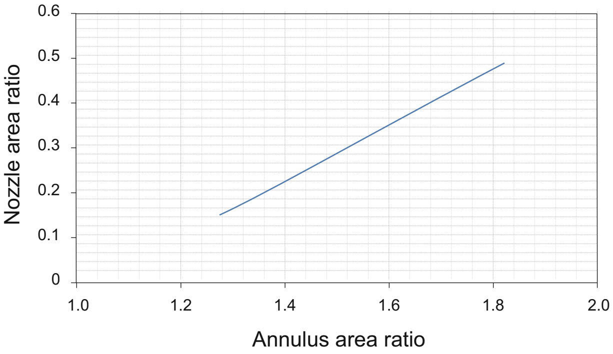

Fig. 3 Relationship between nozzle area ratio and annulus area ratio (0.114-0.127 m pipe, 0.146-0.159 m collar and 3×20 bit nozzles)

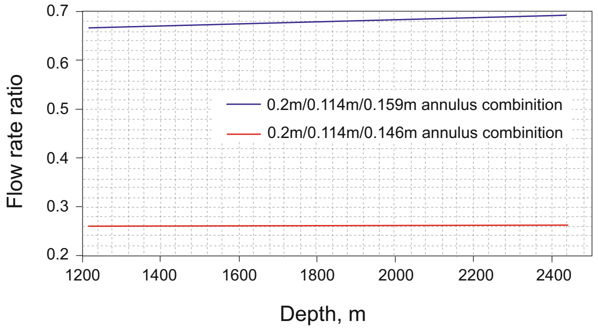

Fig. 4 Change of flow rate ratio with depth (constant energy = 1,850 J/m^3) for 3×20 bit nozzles

2.5 Bit orifice optimization

Excessive gas flow velocity through the bit can cause several problems including borehole erosion, hole deviation, and ice-balling of drill bit (Guo and Liu, 2011). These problems are usually associated with sonic flow condition at the bit. The most detrimental effect of sonic flow is its pressure-barrier effect (Guo and Ghalambor, 2005). Under sonic flow conditions, the pressure build up in the annulus due to cuttings accumulation cannot be detected by reading the standpipe pressure. The cuttings bed will continue to build in the annulus and the drill string eventually get stuck. The boundary between the sonic flow and subsonic flow is identified by a downstream to upstream pressure ratio of about 0.53 for most gases used in gas drilling. Guo and Liu (2011) give an expression of the minimum bit nozzle area without causing sonic flow as:

$$A_n = \frac{Q_{g0}}{p_{dn}}\sqrt{S_g\left(t_{up} + 273.15\right)} \tag{15}$$

where

A_n = total cross-sectional area of the nozzles, m^2

p_{dn} = downstream pressure, Pa

t_{up} = upstream temperature, °C

2.6 Depression of formation water

The excess production of formation water has been generally recognized a major problem that hinders drilling with gas. The current practice of mitigating the problem is to use foams or high-rate gas injection for liquid removal, both of which have limitations due to operating cost. Guo et al (2013) proposes to use water injection to depress formation water influx. The required amount of water injection rate can be determined using NODAL analysis approach.

NODAL analysis is a technique patented by Schlumberger for simulation of multiphase flow in pipes. It is based on system analysis in chemical engineering. Guo et al (2007) provides a comprehensive description of the technique applied to oil and gas production systems. One type of NODAL analysis involves simultaneous solution of the inflow performance relationship (IPR) and outflow performance relationship (OPR) functions for predicting fluid flow rate under given flow constraints/conditions. The IPR function for water flow to the wellbore depends on flow regimes including transient flow, pseudo-steady state flow, and steady state flow. It is difficult to choose an IPR model for gas unbalanced drilling (UBD) without knowing the flow conditions inside the formation. Because of this complex nature of water flow inside the formation, IPR models are employed in a way that they have to be calibrated first with field data, which makes it less critical to assume a flow condition. For simplicity of explanation, the following equation presented by Guo et al (2007) was employed by Guo et al (2013) for steady state water flow into vertical wells:

$$p_{wf} = p_e - \frac{Q_w}{J_w} \tag{16}$$

where theoretically for a vertical well

$$J_w = \frac{k_H h}{366565\mu_w B_w\left(\ln\frac{r_e}{r_w} + S\right)} \tag{17}$$

However, the value of water productivity J_w is very often determined on the basis of matching Eq. (16) to the field data.

The IPR function for water flow to horizontal wells may be chosen from several mathematical models. Joshi (1988) presented a mathematical model considering steady-state flow in the horizontal plane and pseudo steady-state flow in the vertical plane. Joshi's equation was modified by Economides et al (1991) to include the effect of reservoir anisotropy. Guo et al (2007) suggest that the equation presented by Furui et al (2003) should be used for reservoir segments of different permeabilities. Furui et al.'s equation can be expressed as:

$$p_{wf} = p_e - \frac{366565\mu_w B_w Q_w}{k_H L}\left\{ I_{ani}\ln\left[\frac{hI_{ani}}{r_w\left(I_{ani}+1\right)}\right] + \frac{\pi y_b}{h} - I_{ani}\left(1.224-s\right)\right\} \tag{18}$$

where

Q_w = water production rate, m^3/hour
h = pay zone thickness, m
p_e = reservoir pressure, MPa
p_{wf} = bottom hole pressure, MPa
$I_{ani} = \sqrt{\dfrac{k_H}{k_V}}$
k_H = horizontal permeability to water, md
k_V = vertical permeability to water, md
r_{eH} = radius of drainage area of horizontal well, m
L = length of horizontal wellbore, m
B_w = water formation volume factor, rm^3/m^3
μ_w = water viscosity, mPa·s
s = skin factor, dimensionless

The OPR function for gas-water-formation liquid-solid 4-phase flow in wells depends on flow regimes, including mist flow, annular flow, slug flow, and bubbly flow. Eq. (1) for mist flow can be employed.

At a given well depth, the IPR and OPR functions can be combined to solve for the water influx rate Q_w. Both graphical and analytical procedures can be utilized. When a graphical procedure is employed, the IPR function is used to plot bottom hole pressure versus water influx rate, or an IPR curve. The OPR function is used to plot the bottom hole pressure versus water influx rate, or an OPR curve. If these two curves are plotted in the same scale in the same graph, the coordinate of the intersection point of the two curves will give the expected water influx rate and the corresponding bottom hole pressure. When an analytical approach is taken, the bottom hole pressure is eliminated and the water influx rate is solved using a numerical algorithm such as the bisection method or Newton-Raphson iteration which is coded in MS Excel as the Goal Seek tool. Fig. 5 shows a typical bubble map of reduced water influx rate generated by the NODAL analysis technique. It demonstrates that the formation water influx can be effectively depressed by increasing water and gas injection rates.

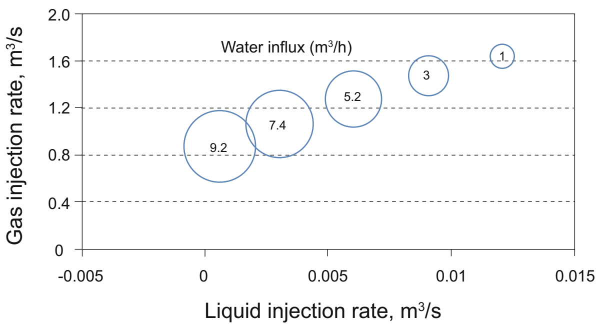

Fig. 5 A calculated bubble map of reduced water influx rate using the NODAL analysis technique

2.7 Bit-rock interaction

The interaction between the drill bit and the formation rock determines the path of the well trajectory and the rate of penetration. Gao and Zheng (2011) reported their studies of the mechanism and control of well deviation in air drilling based on analytical modeling. They concluded that the bottom hole assembly (BHA) behavior in air drilling is almost the same as that in liquid drilling. However, both the formation anisotropy index and the depth of bit tooth invasion in air drilling are higher than that in liquid drilling. The formation anisotropy is the primary reason for well deviation and the greater value of invasion depth of bit teeth in air drilling aggravates the hole deviation. For the purpose of deviation control, BHAs with air hammers and compound-driven pendulum assemblies are recommended for gas drilling operations. The model is not described in this section due to the length limitation of this paper.

Zhang et al (2013) developed a triaxial rate of penetration model for gas drilling. The model considers the effects of drilling parameters, bore hole geometry, bit anisotropy, formation anisotropy, and the bottom hole differential pressure on rate of penetration. They found that the bottom hole differential pressure and formation dip angle have significant effects on the formation forces and thus borehole direction. Their model predicted the well path and rate of penetration for a well in China with remarkable accuracy. The model is not described here due to its mathematical complexity.

3 Summary

Gas drilling design and practice are supported by a suite of theories developed from engineering fundamentals. These theories evolve with time to solve new problems encountered in drilling new types of wells such as horizontal wells. Past literature does not provide a complete update of these theories. This paper reviews the new theories developed in recent years in the areas of multi-phase flow hydraulics in deviated and horizontal boreholes, hole cleaning of solids accumulation, hole cleaning of formation water, flow diverging for washout control, bit orifice optimization, and formation water depression. The updated theories are outlined as follows:

1) The hydraulics of 4-phase flow (injected gas, injected water, formation water/oil, and solids) in vertical, inclined, and horizontal boreholes can be modeled by the recent

analytical solution given by Guo and Liu (2011).

2) Hole cleaning of drill cuttings in gas drilling can be analyzed using the newly developed mathematical model presented by Li et al (2013). The model considers the total gas energy required for lifting cuttings and grinding cuttings.

3) Hole cleaning of formation water influx in gas drilling can be analyzed utilizing the mathematical model presented by Guo et al (2008). The model considers both liquid density and interfacial tension between liquid and gas phases.

4) The gas flow diverging theory established by Li et al (2013) can be employed to design gas diverging nozzles for reducing borehole washout problems. The flow diverging joint should be selected from those that only create jet velocity in the axial direction.

5) The drill bit nozzle area should be designed large enough to avoid sonic flow of gas to reduce drilling problems. The equation presented by Guo and Liu (2011) gives the minimum bit nozzle area without causing sonic flow.

6) Adding water to the gas stream will depress formation water influx. The amount of water to be injected can be determined using the NODAL analysis technique with the equations presented by Guo et al (2013).

7) Bit-rock interaction affects hole deviation and rate of penetration more significantly in gas drilling than in liquid drilling. Gao and Zheng's (2011) model and its updated version by Zhang et al (2013) can be used for prediction and control of well path.

Acknowledgements

This research was financially supported by the National Natural Science Foundation of China through Grants No. 51221003, No. 51134004 and No. 51274220.

References

Adewumi M A and Tian S. Hydrodynamic modeling of wellbore hydraulics in air drilling. Paper SPE 19333 presented at the SPE Eastern Regional Meeting, 23-24 August 1989, Columbus, Ohio

Allan P O. Nitrogen drilling system for gas drilling applications. Paper SPE 28320 presented at the SPE 69th Annual Technical Conference and Exhibition, 25-28 September 1994, New Orleans, Louisiana

Angel R R. Volume requirements for air or gas drilling. Trans. AIME. 1957. 210: 325-330

Capes C E and Nakamura K. Vertical pneumatic conveying: an experimental study with particles in the intermediate and turbulent flow regimes. Canadian Journal of Chemical Engineering. 1973 (June): 33-38

Economides M J, Deimbacher F X, Brand C W, et al. Comprehensive simulation of horizontal well performance. SPE Formation Evaluation. 1991. (Dec.): 418-426

Furui K, Zhu D and Hill A D. A rigorous formation damage skin factor and reservoir inflow model for a horizontal well. SPERE. 2003. (Aug.): 151-155

Gao D and Zheng D. Study of a mechanism for well deviation in air drilling and its control. Petroleum Science and Technology. 2011. 29(4): 358-365

Gas Research Institute (GRI). Underbalanced Drilling Manual. Chicago. Gas Research Institute Publication. 1997. 88-94

Gray K E. The cutting carrying capacity of air at pressures above atmospheric. Trans. AIME. 1958. 213: 180-185

Guo B and Ghalambor A. Gas Volume Requirements for Underbalanced Drilling Deviated Holes. Tulsa: PennWell Books. 2002. 67-71

Guo B and Ghalambor A. Natural Gas Engineering Handbook. Houston: Gulf Publishing Company. 2005. 95-102

Guo B and Liu G. Applied Drilling Circulation Systems. Oxford: Elsevier. 2011. 145-150

Guo B, Hareland G and Rajtar J. Computer simulation predicts unfavorable mud rate and optimum air injection rate for aerated mud drilling. SPE Drilling & Completion Journal. 1996. (June): 22-28

Guo B, Li J, Meng Y, et al. Use of NODAL analysis method for optimizing nitrogen injection rate to minimize water influx in shale gas drilling. Paper SPE/IADC 166710, proceedings (in press) of the SPE/IADC Middle East Drilling Technology Conference and Exhibition to be held 7-9 October 2013, Dubai, UAE

Guo B, Lyons W C and Ghalambor A. Petroleum Production Engineering. Oxford: Elsevier. 2007. 172-175

Guo B, Miska S and Lee R L. Volume requirements for directional air drilling. Paper IADC/SPE 27510 presented at the IADC/SPE Drilling Conference, 15-18 February 1994, Dallas, Texas

Guo B, Yao Y and Ai C. Liquid carrying capacity of gas in underbalanced drilling. Paper SPE 113972 presented at the SPE Western Regional Meeting, 31 March to 2 April 2008, Los Angeles, California

Guo B, Zhang Z and Gao D. Optimal use of flow-diverting joint in underbalanced gas drilling. Paper SPE 143309 presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, 20-22 September 2011, Jakarta, Indonesia

Ikoku C U, Azar J J and Williams C R. Practical approach to volume requirements for air and gas drilling. Paper SPE 9445 presented at the SPE 55th Annual Fall Technical Conference and Exhibition, 2-5 October 1980, Dallas, TX

Joshi S D. Augmentation of well productivity with slant and horizontal wells. Journal of Petroleum Technologies. 1988. (June): 729-739

Li J, Guo B, Liu G, et al. The optimum range of nitrogen injection rate in shale gas well drilling. SPE Drilling & Completion. 2013. 28(1): 12-15

Li J, Yang S, Guo B, et al. Distribution of the sizes of rock cuttings in gas drilling at various depths. Computer Modeling in Engineering & Sciences (CMES). 2012. 89(2): 79-96

Lyons W C, Guo B and Seidel F A. Air and Gas Drilling Manual (2nd Edition). New York: McGraw-Hill. 2001. 55-59

Lyons W C, Guo B, Graham R L, et al. Air and Gas Drilling Manual (3rd Edition). Amsterdam: Elsevier. 2009. 77-81

Machado C J and Ikoku C U. Experimental determination of solid fraction and minimum volume requirements in air and gas drilling. Journal of Petroleum Technology. 1982. (Sept.): 35-42

Martin D J. Use of air or gas as a circulating fluid in rotary drilling—volumetric requirements. Hughes Engineering Bulletin. 1952. 23: 35-42

McCray A W and Cole F W. Oil Well Drilling Technology. Edmund: University of Oklahoma Press. 1959. 44-49

Mitchell R F. Simulation of air and mist drilling for geothermal wells. Journal of Petroleum Technology. 1983. (June): 27-34

Puon P S and Ameri S. Simplified approach to air drilling operations. Paper SPE 13380 presented at Eastern Regional Meeting, 1 October to 2 November 1984, Charleston, West Virginia

Schoeppel R J and Spare A R. Volume requirements in air drilling. Paper SPE 1700-MS presented at Drilling and Rock Mechanics Conference, 25-26 January 1967, Austin, Texas

Sharma M P and Chowdry D V. A computational model for drilled cutting transport in air (or gas) drilling operations. Paper SPE 12236 presented at the SPE Southeast Conference on Theoretical and Applied Mechanics, 6-7 September 1984, Dallas, Texas

Sharma M P and Crowe C T. A novel physic-computational model for quasi one dimensional gas-particle flows. Trans. ASME. 1977. 22: 79-83

Singer C. History of Technology. London: Oxford Press. 1958. 66-71

Tian S and Adewumi M A. Development of hydrodynamic model-based air drilling design procedures. Paper SPE 23426 presented at proceedings of the SPE Eastern Regional Meeting, 26-28 October 1991, Columbus , Ohio

Turner R G, Hubbard M G and Dukler A E. Analysis and prediction of minimum flow rate for the continuous removal of liquids from gas wells. Trans. AIME. 1969. 246: 1475-1479

Wolcott P S and Sharma M P. Analysis of air drilling circulating systems with application to air volume requirement estimation. Paper SPE 15950 presented at the SPE Eastern Regional Meeting, 28-30 October 1986, Columbus, Ohio

Yost II A B, Carden R, Muncey J G, et al. Air drilling and multiple hydraulic fracturing of a 72° slant well in Devonian shale. Paper SPE 21264 presented at the SPE Eastern Regional Meeting, 31 October to 2 November 1990, Columbus, Ohio

Zhang H, Gao D and Xie X. Research on a triaxial rate of penetration (ROP) model related to unloading in oil & gas drilling. Computer Modeling in Engineering & Sciences (CMES). 2013. 90(1): 47-63

(Edited by Sun Yanhua)