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A Novel Study for Shock Wave Phenomenon during Gas Drilling Process

Peibin Gong[a], Zhiyuan Wang[b], Yin Zhang[c]*, Xiuliang Yan[a], Zongqing Li[a], and Shirish Patil[c]

a:Underbalanced Drilling Technology Research Department, Drilling Technology Research Institute, Shengli Petroleum Engineering Ltd., Sinopec, Dongying, China, 257100

b:Scholl of Petroleum Engineering, China University of Petroleum(East China), Qingdao, China, 266555

c:Petroleum Engineering, College of Engineering and Mines, University of Alaska Fairbanks, Fairbanks, USA, 99775

Abstract

Gas drilling has been widely used as an underbalanced drilling technique to develop oil/gas resources owning to its higher ROP and reduced formation damage. However, it is always facing the potential danger of well kick, especially when drilling through the gas layers associated with high pressure and high production rate where shock wave may be generated. Shock wave is a kind of strong compressive wave generated in bore hole due to the fast-moving piston-like mud ring accumulated in the annulus, while uncontrolled shock wave may cause great damage to the drilling operators and project. For example, Qionglai-1 well located in the west of Sichuan Basin, China, had been subjected to an accident of shock wave explosion which had caused one rig personal dead, four people injured and destroyed the whole wellhead devices. Therefore, it is practically important to study the shock wave phenomenon during gas drilling process, though seldom theory has been developed to study it so far. In this study, a theoretical analysis model combining continuity equations, momentum equations and energy equations has been developed to investigate the shock wave phenomenon during gas drilling process, while various influence factors have been analyzed. Finally, feasible well control measures for the shock wave phenomenon have been proposed by applying the newly developed theory to the real case (i.e., Qionglai-1 well). It has been found that the instantaneous high pressure at wellhead resulted from the shock wave is the main disaster mechanism of the shock wave phenomenon. The influence factors for the instantaneous high pressure at wellhead mainly include gas flow rate, moving speed of mud ring and the diameter of blooie line, while the borehole size and ROP also have influence on the instantaneous high pressure at wellhead. In general, the instantaneous high pressure at wellhead increases with the increase of the gas flow rate, moving speed of mud ring, borehole size and ROP, while it decreases by increasing the diameter of blooie line. By applying the newly developed technique to the real case, it has been found that using larger diameter of blooie line is more safe to implement well control when shock wave phenomena occurs. Therefore, keeping lower ROP and using larger diameter of blooie line can control shock-wave phenomenon effectively when drilling through high pressure and high production gas layers by using gas.

Introduction

In 1950s, gas drilling was originated in America as a new technology, while it has been applied worldwide because of its reduced formation damage, prevention of lost circulation and obvious high ROP (Sheffield and Sitzman, 1985; Bennion et al., 1998; Li et al., 2009). Sometimes, an abnormal high pressure gas reservoir is drilled, and the gas would flow into the wellbore immediately since the geological conditions are not clearly understood and the reservoir pressure is not predicted accurately. Once this situation occurs, it is difficult to apply traditional techniques to kill the well (Willis, 1985; Guo, 2008). Along with the invaded gas, some formation water would influx into the well and is mixed with the drilling cuttings, while it is generally difficult to circulate the mixture out of the annulus since the mixture tends to attach on the drill pipe and the wall of borehole to form a piston-like mud ring (Fubin et al., 2010). With the development of the mud ring, it will eventually block the annulus; and then an abnormal high pressure may be resulted from the accumulation of the invaded gas under the piston-like mud ring, which provides the primary condition for the development of shock wave (Robert and Oscar, 2002). Shock wave may cause wellhead failure or even the gas well out of control if it is not handled properly.

Qionglai-1 well was a wildcat well located in Sichuan Basin, China, while the main stratum in this area is Xujiahe formation. The designed well depth is 4,680 m, while gas drilling technique was applied to drill the third section associated with the wellbore diameter of 12¼". The well was drilled smoothly to the depth of 2,143 m where the bit bouncing occurred. Correspondingly, the rotary table was rotated reversely to release the drill string torque. During this process, an amount of wet dust spread all over the drill platform, while a harsh sonic boom under the rotary table was heard and an amount of wet dust rushed into the air. During tripping out, a violent explosion happened at the wellhead, which caused one people die and four people injure. According to the official accident notification, this accident may be resulted from the unpredicted natural gas reservoir associated with high pressure and high production rate. However, in general, only the impact force of natural gas hardly can destroy the wellhead. Therefore, it is believed that the wellhead pressure was elevated significantly due to the special phenomenon which is considered to be the shock wave phenomenon, while the elevated wellhead pressure exceeded the bearing capacity of the wellhead, causing the explosion. This is a novel idea to analyze the risks of well control during gas drilling, while, to our knowledge, there are few studies to analyze the destructive mechanisms of the shock wave during gas drilling.

In order to fill this gap, therefore, in this study, the generation mechanism of shock wave inside the wellbore during the gas drilling has been investigated. Then, the characteristics of the shock wave are described, and a method to calculate the significantly elevated wellhead pressure due to shock waves has been proposed. Subsequently, the factors including gas flow rate, ROP, mud ring velocity, diameter of blooie line and wellbore size, which influence the elevated wellhead pressure, has been analyzed by applying the developed method. Finally, the developed method has been applied to a case study (i.e., Qionglai-1 well) to propose the feasible measures to prevent shock wave disaster.

Methodology

Generation Mechanism of Shock Wave during Gas Drilling

During gas drilling process, the Rate of Penetration (ROP) will increase significantly when drilling in the unconsolidated formation associated with abnormal high pressure. Accordingly, more drill cuttings associated with water production will enter the annulus of the wellbore. If the drill cuttings cannot be circulated out the annulus efficiently, by contacting and mixing with produced water, they may bridge between the drillpipe and wellbore in the annulus. With the aggregation of the drilling cuttings, a piston-like mud ring may be eventually developed, as shown in Figure 1, which will block the annulus and cut off the normal circulation. Due to the block-up of the mud ring, the pressure under the mud ring will be elevated significantly. Once the mud ring is set free, it will move up with significant acceleration, while the piston-like mud ring can achieve extremely high speed in a very short time. In the process of accelerated movement of the mud ring, once the velocity of the piston-like mud ring exceeds the gas velocity above the mud ring, a series of compression waves will be generated (Wang et al., 2005; Tang et al., 2011).

The compression waves do not travel upward at the same absolute velocity, while the later generated compression wave travels faster than the previously generated compression wave (Wang et al., 2005; Tang et al., 2011). Thus, once the later generated compression wave catches up the previously generated wave eventually, superposition effect will be caused resulting in stronger shock wave associated with significant energy, as shown in Figure 1. Due to the generation of shock wave, the pressure after the shock wave surface (p_2) is elevated significantly, while the pressure prior to the shock wave surface (p_1) is considered to be unchanged (Wang et al., 2005; Tang et al., 2011). When the shock wave travels to the wellhead, the significantly elevated pressure after the shock wave surface (i.e., p_2) will act on the wellhead and it can be treated as the currently elevated wellhead pressure. Once the currently elevated wellhead pressure (i.e., p_2) exceeds the anti-pressure capacity of the BOP, wellhead damage/explosion will be caused, which is believed to be the main mechanism of shock wave disaster during gas drilling. Therefore, next, a mathematical mode has been developed to calculate the currently elevated wellhead pressure (i.e., p_2), while various influence factors for the elevated wellhead pressure have been analyzed.

Mathematical Model

In order to calculate the elevated wellhead pressure resulted from shock wave, a mathematical model has been developed, while there are several basic assumptions associated with the mathematical model:

1) The multiphase flow in wellbore annulus is considered as one-dimensional flow along the borehole axis;
2) The generated shock wave is simple normal shock wave;
3) The gas in the wellbore is treated as ideal gas, and the adiabatic index of the gas is constant;
4) The pressure under the piston-like mud ring remains constant during the acceleration process of the mud ring, and equals the reservoir pressure;
5) The friction force acting on the mud ring keeps constant.

Due to the generation of shock wave, some gas properties, such as flow velocity and pressure, on both sides of the shock wave surface may be changed significantly (Robert and Oscar, 2002; Wang et al., 2005; Tang et al., 2011), while these changes can be described by the following equations:

Continuity equation:

$$\frac{\partial \rho_1}{\partial t} + \frac{\partial(\rho_1 u_1)}{\partial s} = \frac{\partial \rho_2}{\partial t} + \frac{\partial(\rho_2 u_2)}{\partial s} \tag{1}$$

where the subscript 1 and 2 represent the gas state properties prior to and after the shock wave surface, ρ is the density of gas in kg/m^3, u is the gas velocity in m/s, t is time in second and s is the depth of well in m.

Momentum equation:

$$\frac{\partial u_1}{\partial t}+\frac{1}{\rho}\frac{\partial p_1}{\partial s}=\frac{\partial u_2}{\partial t}+\frac{1}{\rho}\frac{\partial p_2}{\partial s} \tag{2}$$

where p is the gas pressure in Pa.

Energy conservation equation (Wang et al., 2005):

$$h_1+\frac{1}{2}u_1^2=h_2+\frac{1}{2}u_2^2 \tag{3}$$

where h is the enthalpy of the gas in J/kg, while it can be expressed as,

$$h=c_pT=\frac{\kappa}{\kappa-1}RT \tag{4}$$

where c_p is the specific heat at constant pressure in J/(kg•K), T is the temperature in K, R is the gas law constant in J/(kg•K), and κ is the non-dimension gas adiabatic index.

Perfect state equation (Wang et al., 2005):

$$p=\rho RT \tag{5}$$

Prandtl relation (Wang et al., 2005):

$$u_1u_2=V_{cr}^2 \tag{6}$$

where V_{cr} is critical speed of sound in m/s, while there exists an relationship between the V_{cr} and u_1 (Wang et al., 2005),

$$\frac{V_1^2}{\kappa-1}+\frac{u_1^2}{2}=\frac{V_{cr}^2}{\kappa-1}+\frac{V_{cr}^2}{2} \tag{7}$$

where V_1 represents local sound velocity prior to shock wave surface, while it can be calculated as (Wang et al., 2005),

$$V_1=\sqrt{\kappa RT/M_g} \tag{8}$$

where M_g is mole molecular weight of gas.

Combining Eqs. (6) and (7), the following equation can be obtained:

$$\frac{u_2}{u_1}=\frac{\kappa-1}{\kappa+1}+\frac{2}{\kappa+1}\frac{1}{M_1^2} \tag{9}$$

where M_1 is Mach number, while it can be calculated as,

$$M_1=u_1/V_1 \tag{10}$$

It has been proven that the shock wave can be generated when M_1 is larger than one (Tang et al., 2011).

Substituting the Eq. (9) into the integral form of the continuity equation (i.e., Eq. (1)), the following equation can be obtained,

$$\frac{\rho_2}{\rho_1}=\frac{u_1}{u_2}=\frac{(\kappa+1)M_1^2}{2+(\kappa-1)M_1^2} \tag{11}$$

Combining Eqs. (1), (2), (5) and (11), the following relationship can be obtained,

$$\frac{p_2}{p_1}=\frac{2\kappa}{\kappa+1}M_1^2-\frac{\kappa-1}{\kappa+1} \tag{12}$$

As can be seen from Eqs. (11) and (12), the Mach number determines the gas properties prior to and after the shock wave surface.

According to previous definition, u_1 and u_2 are used to represent the gas velocity prior to and after the shock wave surface, respectively. If the shock wave surface is chosen as the reference, they can be calculated as,

$$u_1 = u_s - u_0 \tag{13}$$

$$u_2 = u_s - u_b \tag{14}$$

where u_0 is the original gas return velocity in the annulus before shock wave generation, u_s is the propagation velocity of shock wave, u_b is the achieved maximum movement velocity of the piston-like mud ring.

Substituting Eqs. (13) and (14) into Eqs. (1), (2), (11) and (12), the following equation can be obtained,

$$\frac{u_b-u_0}{V_1}=\sqrt{\frac{p_1}{\rho_1}\left(\frac{p_2}{p_1}\right)\left(1-\frac{\rho_1}{\rho_2}\right)}=\frac{2\left(M_1^2-1\right)}{(\kappa+1)M_1} \tag{15}$$

so the March number M_1 can be calculated as,

$$M_1=\frac{(u_b-u_0)(\kappa+1)}{4V_1}+\sqrt{\frac{(u_b-u_0)^2(\kappa+1)^2}{16V_1^2}+1} \tag{16}$$

where u_b can be determined by,

$$u_b=a\cdot\Delta t \tag{17}$$

where Δt is acceleration time in second, while in this study, Δt has been assigned 0.5 s. a is the acceleration of mud ring in m/s^2, while it can be calculated by using the following equation through force analysis on the mud ring as shown in Figure 2,

$$a=\frac{\sum F_r}{m_r}=\frac{(p_R-p_b)\times\frac{\pi}{4}(D_b^2-D_p^2)-G-f}{\rho_r\times\frac{\pi}{4}(D_b^2-D_p^2)\Delta h} \tag{18}$$

where p_R is the pressure under the mud ring in Pa equaling to the reservoir pressure, P_b is the gas pressure acting on the upper side of the mud ring calculated by Eq. (24),, D_b and D_p are the borehole diameter and drilling stem diameter respectively in m, Δh is the thickness of the mud ring in m, G is the gravity of the mud ring, f is frictional force working on the mud ring. As can be seen from Figure 2, the friction force of f can be calculated as (Poselevich, 1977),

$$f=f_1+f_2=\tau\pi D_b\Delta h+\tau\pi D_p\Delta h \tag{19}$$

where τ is the shear stress of the mud ring in Pa, while it can calculated as,

$$\tau=kp_R \tag{20}$$

where k is the dimensionless friction coefficient.

Until now, the March number (i.e., M_1) can be determined, next, p_1 needs to be calculated. It has been assumed that p_1 equals to the original wellhead pressure when the shock wave arrives at the wellhead. Therefore, p_1 equals to the atmospheric pressure (p_0) plus the pressure drop in the blooie line, while it can be expressed as,

$$p_1 = p_0 + \int_0^L \left|\frac{dp}{dl}\right|_{fr} .dl + \frac{\rho_r \xi u^2}{2} \tag{21}$$

where ξ is the local head loss coefficient and it is dimensionless, p_0 is the atmospheric pressure at the ground in Pa, L is the length of the blooie line in m, u is the gas velocity in the blooie line in m/s, $\left|\frac{dp}{dl}\right|_{fr}$ is the friction pressure gradient in the blooie line in Pa/m; ρ_r is the density of the gas-solid mixture in the blooie line, while it can be determined by,

$$\rho_r = \rho_g (1-\alpha) + \rho_c \alpha \tag{22}$$

where ρ_g is the gas density, kg/m^3, ρ_c is the rock density in kg/m^3, α is the cutting volume fraction in (%) which can be calculated as (Yu, 2010),

$$\alpha = \frac{\pi v_{pc} D_{bit}^2}{\pi v_{pc} D_{bit}^2 + 4Q_{sc} p_0 T/(pT_0)} \tag{23}$$

where v_{pc} is the ROP of gas drilling in m/s, D_{bit} is bit diameter in m, p is the pressure at the calculation point in MPa, T_0 is the temperature at standard condition in K, T is the temperature at the calculation point in K, Q_{sc} is the gas flow rate at the standard condition in m^3/min and it can be obtained by surface gas flow meter.

Now, the pressure acted on the upper surface of the mud ring can be calculated as,

$$p_b = p_1 + \int_0^H \left|\frac{dp}{dl}\right|_{fr} .dh \tag{24}$$

where H is the current mud ring depth in m, and p_1 is the well head pressure in Pa.

The procedure of the technique proposed in this study has been briefly described as follows,

1) Record the data of the gas flow meter and convert to gas flow rate, then p_1 and p_b can be calculated by using Eq.(21) to Eq.(23), and Eq.(24) respectively;
2) Calculate the initial gas velocity at well head u_0 according to the equation of gas state at boolie line and well head, respectively;
3) Calculate the velocity of the piston-like mud ring, u_b, using Eq.(17) to Eq.(20);
4) Calculate the local sound velocity prior to shock wave surface, V_1 , using Eq.(8);
5) Calculate the March number, M_1, from Eq.(16);
6) Calculate the elevated wellhead pressure, p_2, using Eq.(12).

Results and Discussion

Influence Factors Analysis

In this subsection, the developed methodology has been applied to analyze the influence of various parameters including the borehole size, gas flow rate, piston-like mud ring move velocity, ROP and blooie line size on the elevated wellhead pressure, i.e., the elevated pressure after the shock wave surface, p_2. The basic drilling parameters used in the calculation have been tabulated in Table 1, while the influence of various parameters on the p_2 have been described in Figures 3 to 6.

As can be seen from Figures 3, 5 and 6, the gas flow rate has significant influence on the elevated wellhead pressure (p_2), while wellhead pressure would be elevated more significantly with increasing gas flow rate in the blooie line. Accordingly, at extreme high gas flow rate, the elevated wellhead pressure (p_2) may be high enough to destroy the wellhead directly. And Figure 3 shows that the wellhead pressure would be elevated more with increasing wellbore diameter. It can be seen from Figure 4 that, under fixed gas flow rate (in this study, the gas flow rate is fixed at 120×10^4 m^3/d), when the shock wave travels to the wellhead, it would result in higher wellhead pressure with increasing move velocity of mud ring which is affected by reservoir pressure and original wellhead pressure. In addition to the influence of gas flow rate on the elevated wellhead pressure, Figure 5 depicts the influence of ROP on the elevated wellhead pressure, while, as can be seen, under the same gas flow rate, higher wellhead pressure would be resulted from shock wave with increasing ROP. Besides, blooie line diameter has significant influence on the elevated wellhead pressure as it impacts the pressure drop in the blooie line further affecting the original wellhead pressure, i.e., the pressure prior to shock wave surface, p_1. Obviously, as can be seen from Figure 6, under the same gas flow rate, the wellhead pressure would be elevated more significantly by decreasing blooie line diameter. From the above analysis, the instantaneous elevated pressure at wellhead resulted from shock wave increases with the increase of the gas flow rate, moving speed of mud ring, borehole size and ROP, while it decreases by increasing the diameter of blooie line. As we know, during the drilling, the gas flow rate, moving speed of mud ring and borehole size are uncontrollable parameters, therefore, the ROP and blooie line diameter are feasibly controlled to reduce the instantaneous elevated pressure at wellhead resulted from shock wave. Finally, it is suggested that when drilling through the abnormal high pressure gas zone where shock wave may be generated, it is safer to drill at lower ROP associated with larger diameter of blooie line.

Case Study

In this subsection, the developed methodology has been applied to analyze the potential explosion reason of the Qionglai-1 well. The basic drilling parameters of

Qionglai-1 well used for calculation have been tabulated in Table 2. Besides, the thickness of the mud ring is assumed to be 30cm, while the acceleration time is assumed to be 0.5s. Accordingly, the acceleration of the mud ring can be calculated as 1088 m/s^2, while, in 0.5 s, the piston-like mud ring can achieve velocity of 544 m/s. Under these conditions, the pressure after the generated shock wave can be elevated to be 5.2 MPa. Therefore, when the shock wave travels to the wellhead, the elevated wellhead pressure (5.2 MPa) exceeded the bearing capacity of the BOP which is 5 MPa, which may cause the wellhead explosion of the Qionglai-1 well. The corresponding calculation results have been described in Figure 7. Besides, as can be seen, under the same condition, if using larger diameter of bloolie line, the elevated wellhead pressure can be reduced significantly, which may keep the wellhead safe.

Conclusions

The explosion of Qionglai-1 well located in the west of Sichuan Basin, China has caused personal casualty and great economic loss, while the generation of shock wave has been considered as the main reason for the explosion. Therefore, in this study, the generation mechanism of shock wave during gas drilling has been investigated, while a mathematical model has been developed to calculate the instantaneous elevated wellhead pressure due to shock wave. Then, various influence factors for the elevated wellhead pressure have been investigated. Finally, the developed methodology has been applied for the case of Qionglai-1 well, and feasible well control measures have been proposed. The shock wave may be generated from the superposition of compression wave that may be resulted from the accelerated upward movement of piston-like mud ring formed in the annulus, which results in significantly elevated pressure after the shock wave surface. When the elevated pressure travels to the wellhead and is over the bearing capacity of the wellhead, explosion may occur. It has been found that the instantaneous elevated pressure at wellhead increases with the increase of the gas flow rate, mud ring move velocity, borehole size and ROP, while it decreases by increasing the diameter of blooie line. The explosion of the Qionglai-1 well may be resulted from the fact that the elevated wellhead pressure due to shock wave exceeds the bearing capacity of the wellhead, while increasing the diameter of the bloolie line can reduce the elevated wellhead pressure significantly, which may avoid the wellhead explosion. Therefore, it is feasible to control the elevation of wellhead pressure due to shock wave by reducing ROP and increasing blooie line diameter.

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Table 1. Basic drilling parameters

Parameter	Value	Parameter	Value
Depth(m)	2143.91	Blooie line length(m)	120
Drilling stem diameter(m)	0.127	Blooie line diameter(m)	0.1778
Wellhead temperature(℃)	30	Formation pressure(MPa)	30
Gas relative density	0.65	Temperature gradient(℃/m)	0.03
Rock density(kg/m^3)	2600	Elbow connection angle(°)	90
Borehole size(m)	0.3112	ROP(m/hr)	15

Table 2. Basic drilling parameters of QiongLai-1 well

Parameter	Value	Parameter	Value
Depth(m)	2143.91	Blooie line length(m)	120
Drilling stem diameter(m)	0.127	Blooie line diameter(m)	0.1778
Wellhead temperature(℃)	30	Formation pressure(MPa)	21
Gas relative density	0.65	Temperature gradient(℃/m)	0.03
Rock density(kg/m^3)	2600	Elbow connection angle(°)	90
Number of 90° connection	1	Gas flow rate(m^3/d)	150×10^4
Borehole size(m)	0.3112	ROP(m/hr)	20
Dynamic sealing pressure of rotary control head(MPa)	5	Dimensionless friction coefficient	0.005
Mud ring density(kg/m^3)	2000		

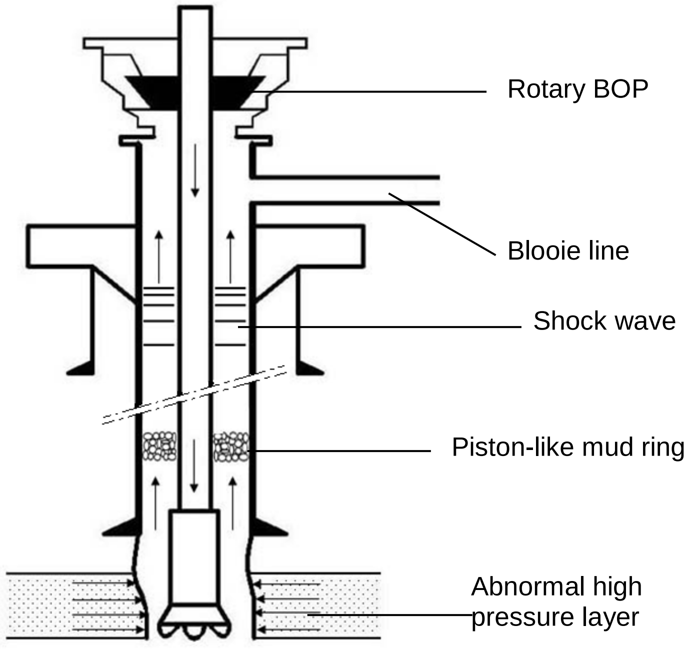

Fig.1 Generation of shock waves during gas drilling

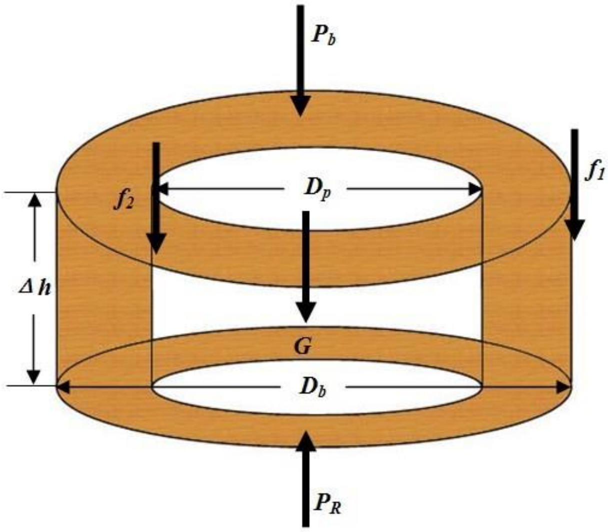

Fig.2 Force analysis of the mud ring

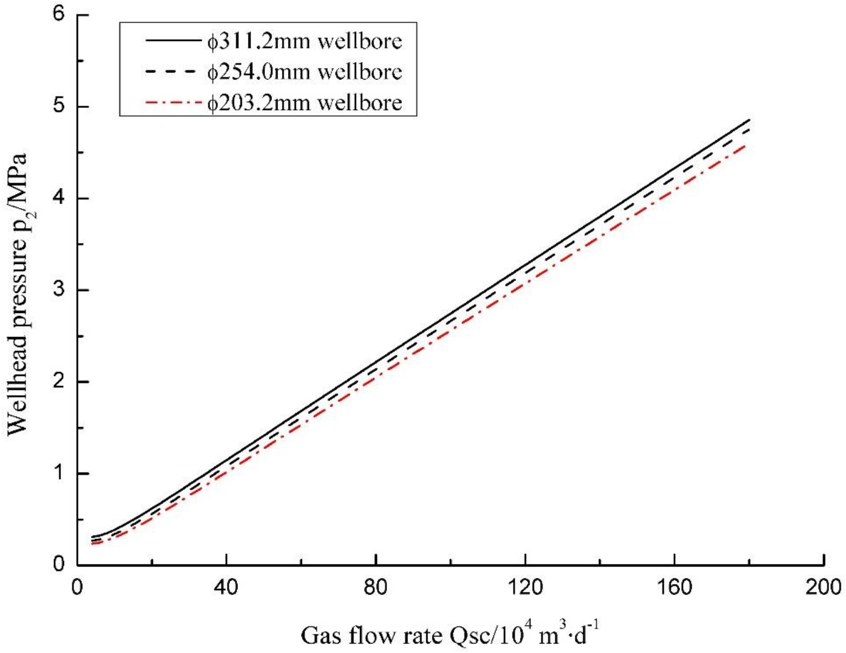

Fig.3 Influence of borehole size and gas flow rate on elevated wellhead pressure, *p*2

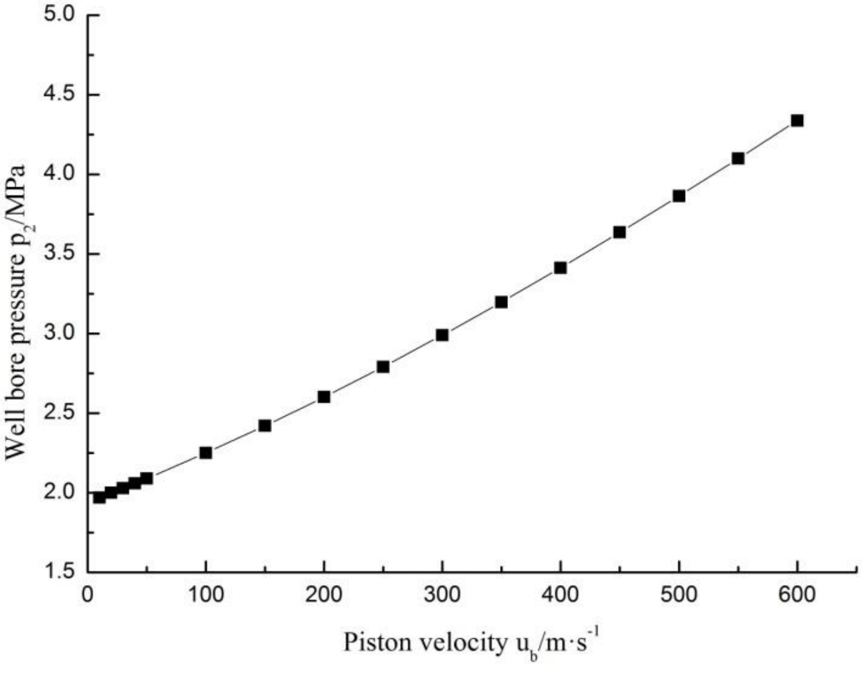

Fig.4 Influence of mud ring move velocity on elevated wellhead pressure, *p*2

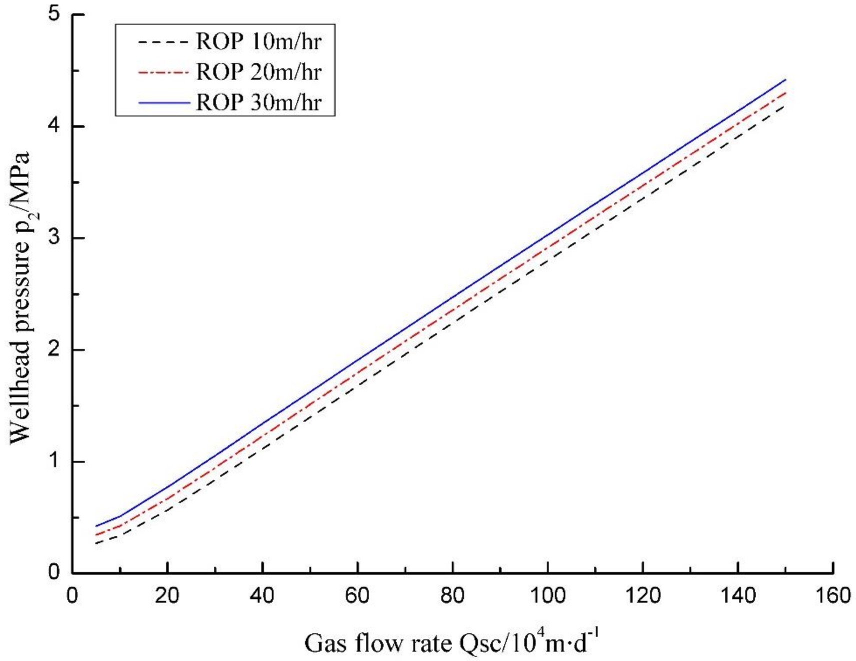

Fig.5 Influence of ROP on elevated wellhead pressure, p_2

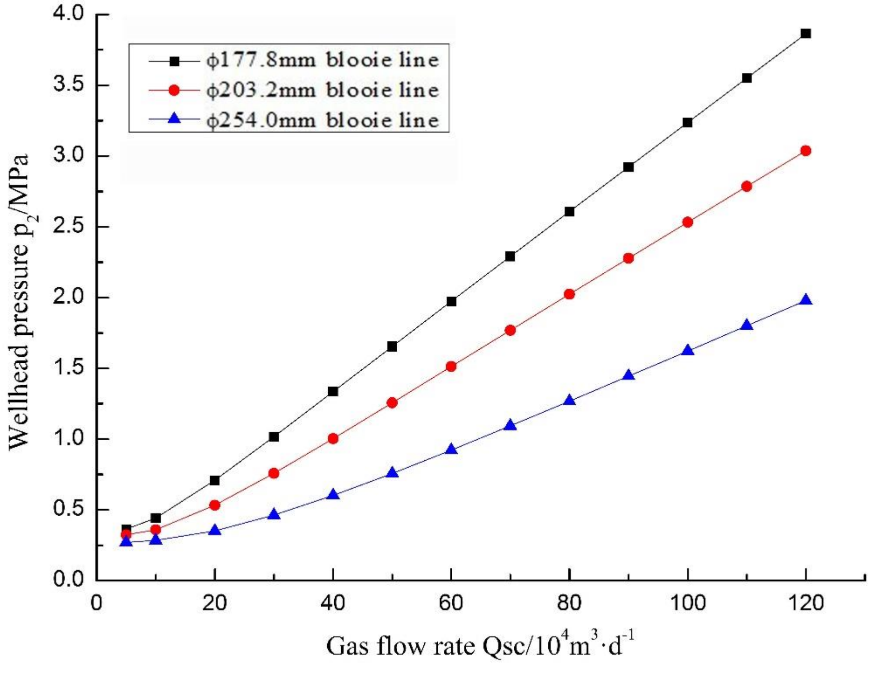

Fig.6 Influence of blooie line diameter on elevated wellhead pressure, p_2

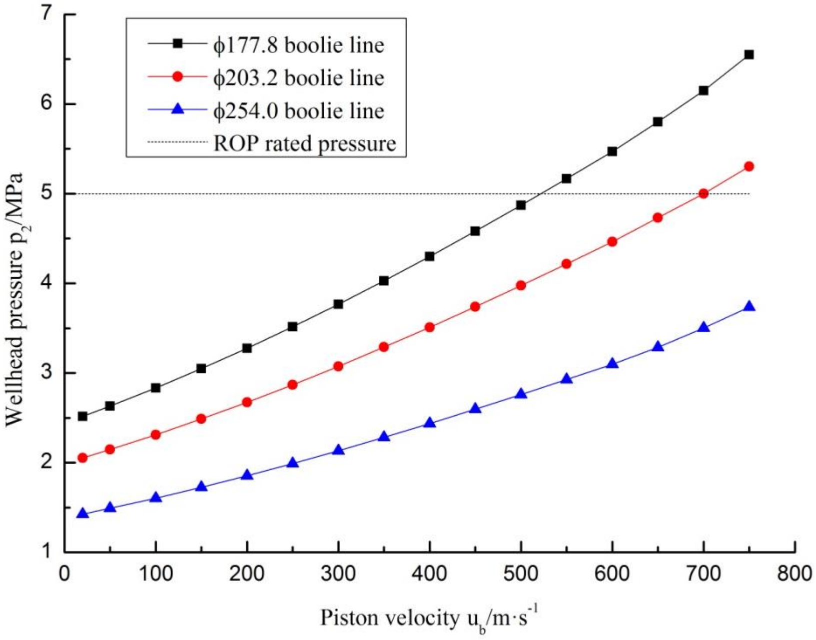

Fig.7 Wellhead pressure when the shock wave came through the wellhead