

Real-time quantitative description of gas invasion in deepwater drilling

Xiaohui Wang, Zhichuan Guan*, Yanan Sheng, Yang Tian

School of Petroleum Engineering, China University of Petroleum, Qingdao, Shandong 266580, China

**Corresponding Author: lunaryyt@163.com (Zhichuan Guan)*

ABSTRACT

With the increase of global deepwater drilling, the scale of the deepwater drilling contract market continues to expand, and the depth of the drilling operations constantly refresh the record. At the same time, the drilling environment and related geological conditions become more and more complex, which leads to the increase of the risk in the operation of deepwater drilling. After the happening of “Deepwater Horizon ” in the Gulf of Mexico, the prevention and control of blowout has become an urgent problem to be solved in the development of offshore oil and gas. Dealing with the problem of overflow and blowout in deepwater drilling, the most effective technical measures are early detection and identification of gas influx. The research on the degree of gas invasion is the basis of the formulation and implementation of well control measures. In this paper, a simulation model of gas-liquid twophase flow after the happening of gas influx is established to calculate the cross section gas content, mud tank overflow and bottom-hole pressure. Through the calculation, the real-time quantitative relationship between the characterization of the gas content and the bottomhole pressure and the increment of the mud pool was established and then the realtime quantitative degree of gas invasion is analyzed.

Keywords: deepwater drilling, gas invasion, real-time detection, numerical simulation, well control

INTRODUCTION

With the continual discoveries of significant oil and gas field in deep water areas, global deepwater oil and gas exploration constantly heat up, and the investment in deepwater oil and gas exploration and development continues to increase. According to Yang (2014), the investment of global deepwater oil and gas exploration and development totaled \$112 billion from 2008 to 2012, and the investment is expected to reach \$223 billion from 2012 to 2017 which is doubled over the last five years. And the investment of deep water well drilling and completion is expected to be \$78 billion.

China is a maritime country, and as an important deep-water oil and gas development zone, South China Sea plays a decisive role in the energy replacement. years, China has actively developed its own deepwater oil and gas development plan and a series of deepwater oil and gas equipment and key technologies as a national major research projects, which has made some achievements (Sun B J, 2011; Geng Y N et al., 2016) In 2010, the sixth generation China offshore drilling platform "offshore oil 981" of China National Offshore Oil Corporation (CNOOC) has been successfully undocked in Shanghai Waigaoqiao Shipbuilding Co. Ltd. In this year, CNOOC offshore capacity is more than 5000*104 t, completing the construction of “maritime DaqingZhang K, 2013.

As the depth of the seawater and drilling operations increase, the drilling environment and

related geological conditions become more and more complex, which leads to the increase of the risk in the operation of deepwater drilling (Fu Jianhong et al., 2015) In 2010, the Gulf of Dalian oil pipeline explosion caused more than 1 thousand and 500 tons of oil into the Gulf of Dalian, China, and this accident a great threat to sea water quality, ecosystem and marine organisms, which finally affect the local fishery, tourism and nearby residents. In the same year, the event of “Deepwater Horizon ” in the Gulf of Mexico caused a sensation all over the world (Hauge S & Qien K, 2012; Cheng R & Wang H, 2013)The disastrous consequences to the ecological environment in this accident caused a serious threat to the Gulf of Mexico's energy strategy and the economic status which brought painful blow to Mexico Bay area and influenced life of the residents in Mexico Bay area. What more, BP Company and BP shareholders suffered heavy losses (Skogdalen J E, Utne I B & Vinnem J E, 2012)

In case of dealing with the problem of overflow and blowout in deepwater drilling, the most effective technical measures are early detection and identification of gas influx (Hargreaves D, Jardine S & Jeffryes B, 2001)There are many research institutions now testing and developing the technology of Detection Method on Marine Riser (DMOMR) to detect gas invasion as soon as possible (Toralde, J. S. S. & Wuest, C. H., 2014; Jonggeun, C., et al., 2007) Considering the serious consequences of gas invasion, even one minute to monitor the occurrence of gas invasion in advance, for the latter part of the well control work is of great significance.

CNOOC Research Institute, Beijing and China University of Petroleum, Beijing have been conducting 3 research projects to develop a gas kick detecting equipment on the riser and testing its signal response. Letton Hall Group had developed a method to testing the density of the drilling fluid using the ultrasonic signals just above the wellhead, at the basis of subsea riser in 2015, aiming to detect the kick earlier than the conventional gas invasion monitoring method at the platform. Through the past ten years, detect the gas influx in the marine section (Geng Y N, 2016)

After the early detection and identification of gas influx, the reasonable well control plan will be put forward according to the risk degree. The research on the degree of gas invasion is the basis of the formulation and implementation of well control measures and at present, there is a lack of research and discussion on this problem. In this paper, an extended two-fluid model (TFM) is developed to describe the gas-liquid two-phase flow (Ghajar, A. J., & Bhagwat, S. M., 2014)when gas influx occurs to calculate the cross section void fraction, mud tank overflow and BHP. Avelar, C. S. (2009) presented a mathematical modeling of a proposed gas kick simulator and made a comparison between simulated and measured results for a test well located in Brazil. Using the mathematical model, a sensitivity analysis regarding the effect of water depth in well control parameters has been done. Wang, Z. Y. (2014) built a simulation model for deepwater gas kicks with consideration of the hydrate phase transition. This model includes the multiphase flow governing equations and the hydrate phase transition calculation equations. Through the calculation, the real-time quantitative relationship between the characterization of the void fraction and the BHP and the increment of the mud pool was established and then the realtime quantitative degree of gas invasion is analyzed.

METHODOLOGY

The fluid flow in the annular when gas influx occurs is generally simplified to a two-phase flow as the low level of cuttings (Nickens, H, V.1987; Hauge, E. et. al., 2013) and it was modeled on the two-fluid model. The major extension from previous gas influx models includes the addition of a modified temperature field of fluid in the annular and several assistant equations (Apak, E. C. & Ozbayoglu, E. M, 2009)

Governing equations

The equation set describes the mass/momentum conservation of intrusive gas and drilling fluid, and the equations of heat transfer and equilibrium.

Immiscible intrusive gas/drilling fluid flow equations

based on the properties of drilling fluid and the surrounding factors are as follows: 1) one-dimensional unsteady flow in the wellbore; 2) compressible gas, incompressible liquid; 3) no mass transfer between liquid and gas; 4) a rigid drill string; 5) concentric drill string and borehole; 6) neglect of annular pressure (Imamura Y, et.al.,2006; Orkiszewski J.,2013). The mass conservation equations for immiscible gas and liquid phases can be written as Equation (1) and Equation (2):

$$\frac{\partial(\rho_g E_g)}{\partial t} + \nabla \cdot (\rho_g E_g \mathbf{v}_g) = S_g \quad (1)$$

$$\frac{\partial[\rho_l(1-E_g)]}{\partial t} + \nabla \cdot [\rho_l(1-E_g)\mathbf{v}_l] = 0 \quad (2)$$

where ρ_g is the gas density (kg/m³); E_g is the gas-bearing ratio (dimensionless); \mathbf{v}_g is the gas velocity (m/s); S_g is the gas source term (kg/(s·m³)); ρ_l is the liquid or drill fluid density (kg/m³); \mathbf{v}_l is the liquid or drill fluid velocity (m/s). Then the total mass conservation equation of the fluid in the wellbore can be obtained

$$\frac{\partial[\rho_g E_g + \rho_l(1-E_g)]}{\partial t} + \nabla \cdot [\rho_g E_g \mathbf{v}_g + \rho_l(1-E_g)\mathbf{v}_l] = S_g \quad (3)$$

Momentum conservation law governs the flow rate of each phase

$$\frac{\partial(\rho_g E_g \mathbf{v}_g)}{\partial t} + \nabla \cdot (\rho_g E_g \mathbf{v}_g^2) = \text{div}(E_g I_g) + \rho_g \mathbf{b} + \mathbf{m}_g \quad (4)$$

$$\frac{\partial[\rho_l(1-E_g)\mathbf{v}_l]}{\partial t} + \nabla \cdot [\rho_l(1-E_g)\mathbf{v}_l^2] = \text{div}[(1-E_g)I_l] + \rho_l \mathbf{b} + \mathbf{m}_l \quad (5)$$

where I_g is the stress tensor of gas phase (Pa); \mathbf{b} is the unit mass force (m/s²); \mathbf{m}_g is the acting force to gas (kg/(m²·s²)); I_l is the stress tensor of liquid phase (Pa); \mathbf{m}_l is the acting force to liquid (kg/(m²·s²)). The total momentum conservation equation of the fluid in the wellbore can be obtained when Equation (4) and Equation (5) are added together.

$$\begin{aligned} & \frac{\partial[\rho_g E_g \mathbf{v}_g + \rho_l(1-E_g)\mathbf{v}_l]}{\partial t} + \nabla \cdot [\rho_g E_g \mathbf{v}_g^2 + \rho_l(1-E_g)\mathbf{v}_l^2] \\ & = \text{div}[E_g I_g + (1-E_g)I_l] + (\rho_g + \rho_l)\mathbf{b} \end{aligned} \quad (6)$$

Intrusive gas/drilling fluid energy equations

In order to describe the temperature field of this deepwater drilling system, it should be divided into 3 parts (see Figure1) as follows: (1) the interior of drill string; (2) the annular between formation and drill string; (3) the annular between seawater and drill string.

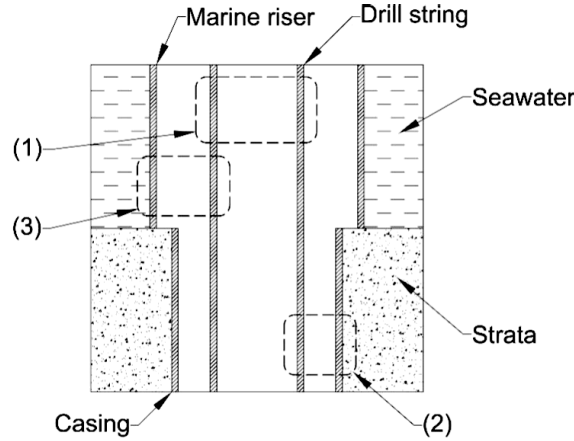


Figure 1. Regional drill pipes and divided heat transfer models

The energy flowing into an element carried by the drill fluid is as follow

$$Q_p(z) = c_l \rho_l(z,t) V T_p(z,t) \tag{7}$$

where Q_p is the energy flowing into an element (W); c_l is the specific heat capacity of liquid or drill fluid (J/(kg·K)); V is the volume of the element and can be calculated as a cylinder volume (m³). The energy flowing out the element carried by the drill fluid is as follow

$$Q_p(z + dz) = c_l \rho_l(z,t) V T_p(z,t) + \frac{\partial [c_l \rho_l(z,t) V T_p(z,t)]}{\partial z} dz \tag{8}$$

Therefore the net energy flowing into an element carried by the drill fluid is

$$Q_p(z) - Q_p(z + dz) = - \frac{\partial [c_l \rho_l(z,t) V T_p(z,t)]}{\partial z} dz \tag{9}$$

The energy from the annular space to the outer wall of the drill string equals the energy from the outer wall of the drill string to its internal wall, and the energy from the internal wall of the drill string to the interior of drill string, which shown as follows

$$Q_{ap} = h_{po} \pi d_{po} dz [\Delta T_a(z,t) - \Delta T_{po}(z,t)] \tag{10}$$

$$Q_{ap} = \frac{2\pi \lambda_p dz [\Delta T_{po}(z,t) - \Delta T_{pi}(z,t)]}{\ln(d_{po}/d_{pi})} \tag{11}$$

$$Q_{ap} = h_{pi} \pi d_{pi} dz [\Delta T_{pi}(z,t) - \Delta T_p(z,t)] \tag{12}$$

where d_{pi} is the inside diameter of drill string (m); ΔT_{po} is the temperature difference in outer wall of drill string (K); ΔT_{pi} is the temperature difference in internal wall of drill string (K); ΔT_p is the temperature difference in drill string (K); h_{pi} is the convection heat transfer coefficient of drill string and inside drill fluid (W/(m²·K)); d_{po} is outside diameter of drill string (m); h_{po} is

convection heat transfer coefficient of drill string and annular drill fluid (W/(m²·K)); λ_p is the thermal conductivity of drill string (W/(m·K)); ΔT_a is the temperature difference in annular (K). The ΔT_{po} and ΔT_{pi} can be eliminated according to Eqs. (10) (11), and the net energy flowing into an element in the part of radial convection heat transfer can be therefore written as follow

$$Q_{ap} = \frac{\pi[\Delta T_a(z,t) - \Delta T_p(z,t)]}{\frac{1}{h_{pi}d_{pi}} + \frac{1}{h_{po}d_{po}} + \frac{\ln(d_{po}/d_{pi})}{2\lambda_p}} \quad (13)$$

Therefore, the energy conservation equation of part (1) in the deepwater drilling temperature system can be written as follow

$$Q_p(z) - Q_p(z+dz) + Q_{ap} - \Phi_{f1} = \frac{\partial Q_p(z,t)}{\partial t} \quad (14)$$

Closure relations

In order to make the equation set close, assistant equations such as equations of state, wall friction force, interfacial drag force, gas inflow rate, convective heat transfer coefficient equations, equations for viscosity and density of gas-liquid two-phase flow, equations for temperature of seawater and strata are all included.

Boundary condition

In the time when the drill bit just reaches the high-pressure gas reservoir area, the gas intends to inflow to the annular. Usually, the gas-bearing ratio and gas velocity are considered as 0 at that time, and the inlet gas and liquid flow rates and outlet pressure are known. Therefore, the corresponding liquid or drill fluid velocity equals the ratio of fluid flow rate and the annular area, and the transient pressure equals the relevant fluid column pressure. The pressure in wellhead can be considered as one bar.

Simulation ase

The consequence of gas influx detection is affected by numerous factors, such water depth, wellbore depth, permeability of the formation, formation equivalent density. The data of an actual well M-1 located in South China Sea is presented in Table1.

Table1 Partial parameters of the formation and drilling operation

Water depth (m)	1500	Inner diameter of marine riser (mm)	475.74	Drill bit diameter (mm)	215.9	Formation permeability (mD)	100
Wellbore depth (m)	2500	Outer diameter of marine riser (mm)	508	Penetration rate (m/h)	8	Formation equivalent density (kg/m ³)	1330
Drill fluid flow (m ³ /s)	0.03	Inner diameter of intermediate casing (mm)	222.38	Outer diameter of drill pipe (mm)	127	Sea surface temperature (°C)	15.0
Drill fluid density (kg/m ³)	1100	Outer diameter of intermediate casing (mm)	244.5	Length of open hole portion (m)	350	Formation geothermal gradient (°C/100m)	3.2

We did the numerical simulation above data, and the law of gas-liquid two-phase flow then obtained.

RESULTS AND DISCUSSION

Validation of the model

Evaluation for validation of each fluid model from the literature was already given in the respective study in the reference. In order to validate the integrated model in this paper, the simulation results of this study for the overflow were compared with the actual data of a well in the South China Sea as a validation process. The related drilling parameters of the well shown in Table 2 (Gao, Y, H., 2007).

Table. 2 Drilling parameters

Water depth/m	1298	Wellbore depth/m	3630
Drill pressure/t	6~4	Rotate speed/rpm	50
Torque/kNžm	15~13	(Delivery rate/(L/s	2701
Pump pressure/MPa	5.2	(Mean drill speed/(m/h	10.8
Diameter of drill collar /mm	120.7	Diameter of non-magnetic drill collar/mm	120.7
Diameter of heavy weight drilling pipe /mm	88.9	Diameter of drilling pipe/mm	127.0
Riser inner diameter/mm	482.6	Riser diameter/mm	533.4

The actual data presented that gas influx occurred during the time of connecting vertical columns, and the overflow was measured to be 2m³. The simulation results of overflow calculated to be 1.89m³ on the related drilling parameters of the well in the South China Sea. Good agreements between the actual data and the simulation results were observed within 5.5%.

Through the numerical simulation, the relationship between void fracture, B.H.P. and overflow can be easily obtained. And the time of gas invasion can be easily found through the calculation of B.H.P. variation with time.

According to the figure of BHP and void fraction vs. overflow and the figure of BHP vs. time of gas invasion, the degree of gas invasion can be well presented. Thus, in the actual operation in the field, no matter the gas invasion is found by means of the mud tank overflow method or by the gas rate monitoring method at the bottom section of the riser, the BHP and gas invasion time can be rapidly calculated by the software in this method after the monitoring signal response, which help have an objective understanding of the degree of gas invasion.

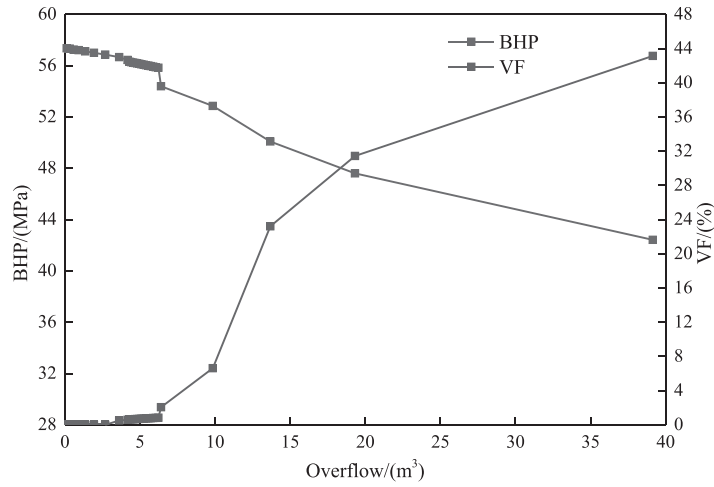


Figure 2. BHP and void fraction vs. overflow

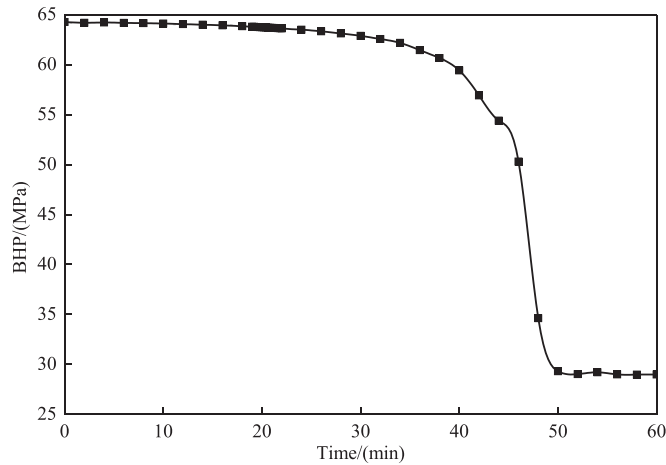


Figure 3. BHP vs. time of gas invasion

The effect of wellbore depth

Figure 4 shows the corresponding relationship between the BHP and void fraction and mud pool overflow under the condition that the seawater depth is 1500m and the wellbore depth 2500m (Figure 4 (a)) and 3500m (Figure 4 (b)) when the gas invasion occurs. In Figure 4 (a), it can be easily found that when the overflow reaches 1m³, the void fraction at the monitoring section reaches 0.4%, and the BHP drop value is 0.07MPa. When the overflow reaches 2m³, the void fraction at the monitoring section reaches 3%, and the BHP drop value is 0.2MPa. At present, the accuracy of acoustic gas invasion monitoring at riser section can reach 0.1%, and the BHP decreased value is only 0.02MPa by this time, which means lower gas invasion degree at this time and the needed mud density in well killing is low. So the risk of well control is greatly reduced. In Figure 4(b), it can be easily found that when the overflow reaches 1m³, the void fraction at the monitoring section reaches 0.2%, and the BHP drop value is 1.6MPa. When the overflow reaches 2m³, the void fraction at the monitoring section reaches 2%, and the BHP drop value is 2.2MPa. According to the

present accuracy of acoustic gas invasion monitoring at riser section, the BHP decreased value is only 1.2MPa by this time, which means lower gas invasion degree at this time.

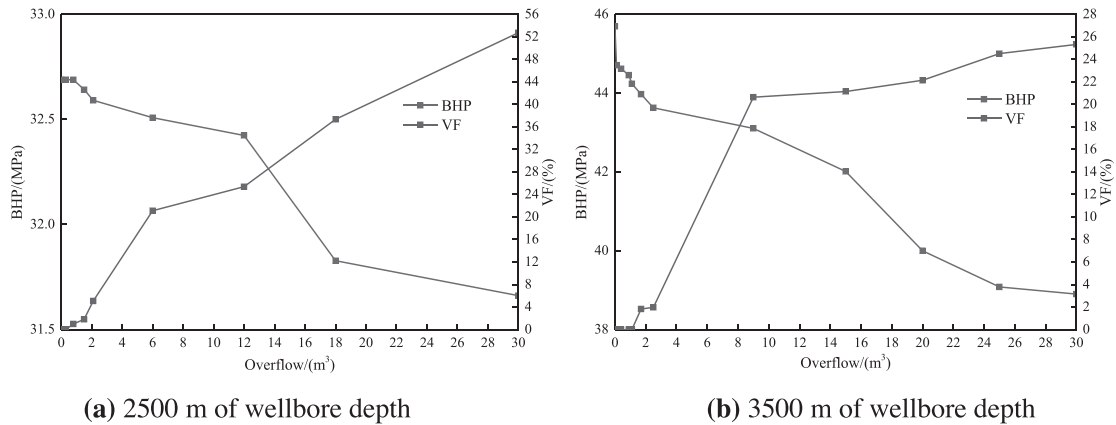


Figure 4. BHP and void fraction vs. overflow at the different wellbore depths

As can be seen from Figure4, the deeper the wellbore depth, the greater the BHP drop-out value when testing the gas invasion which means higher degree of gas invasion and more well control risk. Using the acoustic monitoring method at marine riser can fight for time for the implementation of well control measures which can reduce the degree of gas invasion, thereby reducing the risk of well control.

The effect of formation permeability

Figure5 shows the corresponding relationship between the BHP and void fracture and mud pool overflow under the condition that the formation permeability 100mD (Figure5 (a)) and 300mD (Figure5 (b)) when gas invasion occurs. The higher the formation permeability, the faster the gas rate, and the faster the increment in the mud pool. In Figure5 (a), it can be easily found that when the overflow reaches 1m³, the void fraction at the monitoring section reaches 0.5%, and the BHP drop value is 4MPa. When the overflow reaches 2m³, the void fraction at the monitoring section reaches 8%, and the BHP drop value is 6.5MPa. According to the present accuracy of acoustic gas invasion monitoring at riser section, the BHP decreased value is only 1MPa by this time, which means lower gas invasion degree at this time and the needed mud density in well killing is low. In Figure 5(b), it can be easily found that when the overflow reaches 1m³, the void fraction at the monitoring section reaches 0.02%, and the BHP drop value is 0.2MPa. When the overflow reaches 2m³, the void fraction at the monitoring section reaches 0.03%, and the BHP drop value is 0.4MPa. According to the present accuracy of acoustic gas invasion monitoring at riser section, the BHP decreased value is 0.9MPa by this time, which means higher gas invasion degree at this time. So the needed mud density in well killing is higher and the risk of well control increases.

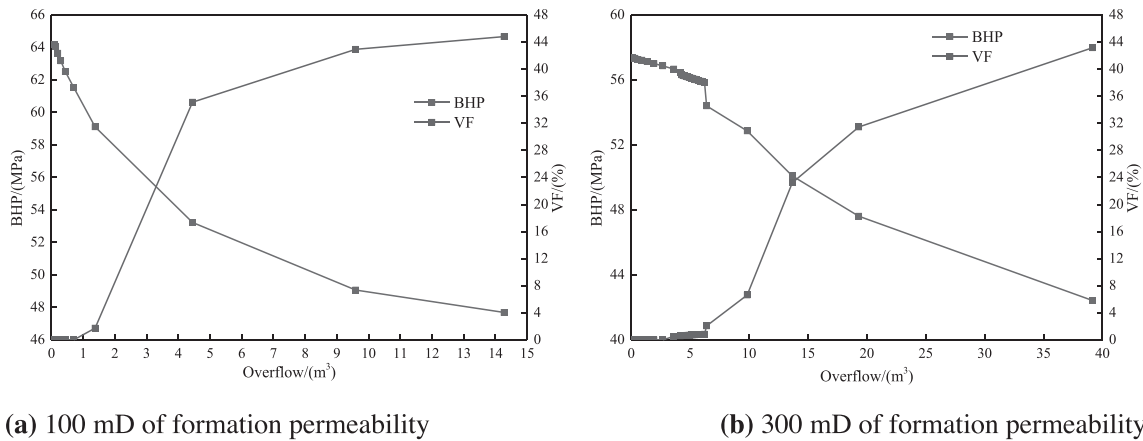


Figure 5. BHP and void fraction vs. overflow at different formation permeability

As can be seen from Figure 5, the greater the permeability, the greater the BHP drop-out value when testing the gas invasion which means higher degree of gas invasion and more well control risk. When the formation permeability is low, the use of acoustic monitoring method at marine riser can fight for time for the implementation of well control measures which can reduce the degree of gas invasion, thereby reducing the risk of well control. When the formation permeability is high, then the method of acoustic monitoring has no advantage.

The effect of formation equivalent density

Figure 6 shows the corresponding relationship under the condition that the formation equivalent density 1330 kg/m³ (Figure 6(a)) and 1350 kg/m³ (Figure 6(b)) when the gas invasion occurs. In Figure 6(a), it can be easily found that when the overflow reaches 1m³, the void fraction at the monitoring section reaches 0.5%, and the BHP drop value is 4MPa. When the overflow reaches 2m³, the void fraction at the monitoring section reaches 8%, and the BHP drop value is 6.5MPa. According to the present accuracy of acoustic gas invasion monitoring at riser section, the BHP decreased value is only 1MPa by this time, which means lower gas invasion degree at this time and the needed mud density in well killing is low. In Figure 6(b), it can be easily found that when the overflow reaches 1m³, the void fraction at the monitoring section reaches 0.01%, and the BHP drop value is 2MPa. When the overflow reaches 2m³, the void fraction at the monitoring section reaches 0.02%, and the BHP drop value is 3MPa.

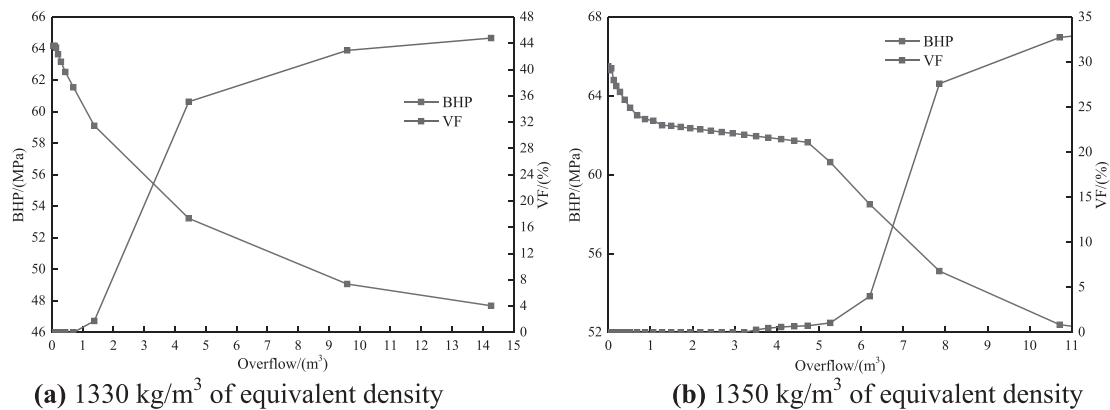


Figure 6. BHP and void fraction vs. overflow at different formation equivalent

As can be seen from Figure 6, the effect of formation equivalent density is similar to formation permeability. When the formation equivalent density is low, the use of acoustic monitoring method at marine riser can fight for time for the implementation of well control measures which can reduce the degree of gas invasion, thereby reducing the risk of well control. When the formation equivalent density is high, then the method of acoustic monitoring has no advantage.

CONCLUSIONS

In this paper, through the establishment of the gas-liquid two-phase flow model, a real-time quantitative relationship between the BHP and void fraction at bottom section and mud tank overflow is established. Then, the change rule between the BHP and void fraction and the mud tank overflow can be obtained under conditions of different well depth, permeability and formation pressure. The deeper the wellbore depth, the greater the BHP drop-out value. When the formation permeability is low, the use of acoustic monitoring method at marine riser can fight for time for the implementation of well control measures. When the formation permeability is high, then the method of acoustic monitoring has no advantage. The greater the equivalent density, the greater the BHP drop-out value when testing the gas invasion. The effect of formation equivalent density is the same as formation permeability.

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وصف كمي لحظي لتدفق الغاز عند الحفر في المياه العميقة

شياوهوي وانج، زيشوان جوان، يانان شينج و يانج تيان
كلية هندسة البترول، جامعة الصين للبترول، تشينغداو، شانغونغ 266580، الصين

الخلاصة

مع زيادة عمليات الحفر في المياه العميقة على مستوى العالم، يستمر حجم سوق التعاقد على حفر الآبار في المياه العميقة في التوسع، كما أن عمق عمليات الحفر يعمل باستمرار على تحديث السجلات. وفي الوقت نفسه، تصبح بيئة الحفر والظروف الجيولوجية ذات الصلة بها أكثر تعقيداً، مما يؤدي إلى زيادة المخاطر في عمليات الحفر في المياه العميقة. فبعد حادثة التسرب النفطي "Deepwater Horizon" في خليج المكسيك، أصبح منع ومكافحة انفجار الآبار مسألة ملحة يجب حلها عند تطوير عمليات التنقيب عن النفط والغاز في البحر. وعند معالجة مشكلة زيادة التدفق والتفجير عند حفر الآبار في المياه العميقة، فإن أكثر الاجراءات الفنية فعالية تعتمد على الكشف المبكر عن إمكانية تدفق الغاز وتحديد موقعه. إن البحث عن درجة تدفق الغاز هو الأساس في صياغة وتنفيذ الإجراءات المناسبة في مراقبة الآبار. في هذا البحث، تم إنشاء نموذج محاكاة لتدفق ثنائي الأطوار من الغاز والسائل بعد حدوث تدفق الغاز وذلك لحساب محتوى الغاز في مقطع مستعرض، والتدفق في خزان التجميع والضغط في قاع البئر. ومن خلال الحسابات، تم تأسيس العلاقة الكمية اللحظية بين خصائص محتوى الغاز وضغط قاع البئر والزيادة في خزان التجميع، ومن ثم تم تحليل الوصف الكمي اللحظي لدرجة تدفق الغاز.