Indian Journal of Geo Marine Sciences
Vol. 49 (02), February 2020, pp. 249-259

Evaluation Method for Probability of Blowout after the Failure of Offshore Well Killing

Bangtang Yin[1,2*], Xuxin Zhang[1,2], Baojiang Sun[1,2], Zhiyuan Wang[1,2], Peibin Gong[3] & Mingzhao Huang[4]

[1]Key Laboratory of Unconventional Oil & Gas Development (China University of Petroleum (East China)),
Ministry of Education, Qingdao, 266 580, China

[2]School of Petroleum Engineering，China University of Petroleum (East China), Qingdao, 266 580, China

[3]Drilling Technology Research Institute, Sinopec Shengli Oilfield Service Corporation, Dongying, 257 000, China

[4]CNPC offshore engineering company limited, Beijing, 100 028, China

[*][E-mail: yinbangtang@163.com]

Received 20 July 2018; revised 10 September 2018

With the development of offshore oil industry, the influx and blowout are inevitable. Well control methods have been well researched, but how to recognize the failure of well control earlier and how to evaluate the probability of blowout for taking steps to avoid are imperfect. Based on the two-phase gas-liquid flow, the characteristic of well killing curve before and after killing are analyzed. Then the method for recognizing the failure of well killing is established by the probabilistic and covariance processing method. Then the blowout due to the failure of well killing is studied and the build-up pressure template is established. According to this, three evaluation methods for blowout probability are established, the shut-off pressure, the standing and casing pressure, formation parameters and underbalanced level varying methods. Final, four hardware systems and one evaluation system are recommended for decreasing or avoiding the risk during the failure of well killing.

[Keywords: Blowout out of control; Evaluation method; Early recognition; The failure of offshore well killing]

Induction

An oil spill following a blowout in the Timor Sea off Western Australia's northern coast is shaping as one of the nation's worst on 21 August 2009 in the Montara oil field[1]. The Deepwater Horizon blowout and oil spill is an industrial disaster that began on 20 April 2010 considered to be the largest marine oil spill in the history of the petroleum industry[2]. The Bohai Bay oil spill was a series of oil spills that began on 4 June 2011 at Bohai Bay, China[3]. Each of these recent accidents has brought about great problems, and not only huge economic losses for offshore oil development and human casualties, but also the destruction of the marine ecological environment. After reviewing the processes of how these accidents were handled, one can conclude that the current state of the blowout risk evolution mechanism in offshore drilling and well-control technology is extremely lacking compared to land drilling.

Offshore drilling attracted global attention since the Macando blowout. Worldwide concern on the safety level of oil and gas industry is raised and the deepwater drilling activity is directly influenced. The probability of drilling abnormal high pressure reservoir is big when the oil and gas exploration area move to deep or ultradeep water, leading to the inevitable overflow, gas kick or blowout. Once the well control is failed, the loss is incalculable. It will cause the influx or blowout even worse and the wellbore pressure system will become more complicated. But the influx, blowout and well control are inevitable with the development of oil industry. So, the well killing is needed for avoiding the more losses. The well control in offshore drilling are different from the methods on the land or shallow water due to the complicated marine environment, reservoir formation characteristics, drilling equipment and technology. There are many factors causing the well control risk and each factor may cause different influence on risk. The assessment on well control risk incentives can reduce the probability of blowout effectively.

Recently, there are lots of studys about the multiphase flow behaviors in wellbore during well control[4-10]. Sule et al.[6] presents a reliability assessment of kick control operation in a constant bottomhole pressure technique of managed pressure using a dynamic annular pressure control system. Aarsnes et al.[7] developed a coupled PDE-ODE model of pressure and distributed gas dynamics during offshore well control. Sun et al.[8] proposed a pattern recognition model for gas kick diagnosis in deepwater drilling. Wang et al[9] established the gas influx mathematical model to finely describe the APWD pressure variation during the gas influx, combining the two dominating phenomena, namely, reduced hydrostatic pressure of the mud column and increased annular pressure due to friction resistance and inertia force. Oliveiraa et al.[10] developed a simplified kick simulator to aid the analysis, through graphics, of the dynamic behavior of some variables, such as volume fractions of both drilling fluid and gas, density of the gas-liquid mixture in the well and pressure. In recent years, the well control method have been well researched, but how to recognize the failure of well control earlier and how to evaluate the probability of blowout for taking steps to avoid the losses are imperfect. There are few literatures available to study the above problem.

Based on the two phase gas liquid flow theory, the behaviors of well killing curve before and after the failure is analyzed. And the method for recognizing the failure of well killing early is established by analyzing the abnormal curve characteristics. Then the shut-in pressure build-up template is established and two different evaluation methods about the probability of the well control failure are studied. Finally, the four hardware systems and one evaluation system are recommended for decreasing or avoiding the risk after the failure of well killing.

The behaviors of well killing curve before and after the well killing failure

The wellbore pressure calculation during the well killing

Gas-liquid two phase flow occurs in the wellbore annuli after the gas influx. Based on the two phase flow theory, considering the wellbore temperature varying, the wellbore pressure calculating model is established. The length of the segment is dH.

(1) The mixture continuity equation

$$\frac{\partial\left(\alpha\rho_g+(1-\alpha)\rho_m\right)}{\partial t}+\frac{\partial\left(\alpha\rho_g v_g+(1-\alpha)\rho_m v_m\right)}{\partial H}=q_{gp} \cdots (1)$$

(2) The mixture momentum equation

$$\frac{\partial\left(\alpha\rho_g v_g+(1-\alpha)\rho_m v_m\right)}{\partial t}+\frac{\partial\left(\alpha\rho_g v_g^2+(1-\alpha)\rho_m v_m^2\right)}{\partial H}+ \\ \frac{\partial p}{\partial H}+\left(\frac{\partial p}{\partial H}\right)_{fr}+\left[\alpha\rho_g+(1-\alpha)\rho_m\right]g=q_{gp} \quad \ldots (2)$$

(3) The wellbore temperature equation

$$T_{fout}=T_{eout}+\exp[A(z_{in}-z_{out})] \\ (T_{fin}-T_{ein}-g_d/A)+g_d/A \quad \ldots (3)$$

where T_{fout} is wellbore fluid temperature, T_{eout} is undisturbed formation temperature at any given depth, z_{in} is total well depth from surface, z_{out} is variable well depth from surface, T_{eih} is undisturbed formation temperature at the bottom hole, T_{fih} undisturbed wellbore temperature at the bottom hole, g_d is geothermal gradient, $A=\frac{2\pi r_{to}U_{to}k_e}{W_t C_{pm}(k_e+f(t)r_{to}U_{to})}$, r_{to} is inside radius of tubing, U_{to} is overall heat transfer coefficient, K_e is thermal conductivity of earth, W_t is total mass flow rate, C_{pm} is specific heat at constant pressure of mixture fluid, f(t) is transient heat-conduction time function for earth. The detail solution method can be seen in the literature[11-14].

The normal well killing curve characteristics

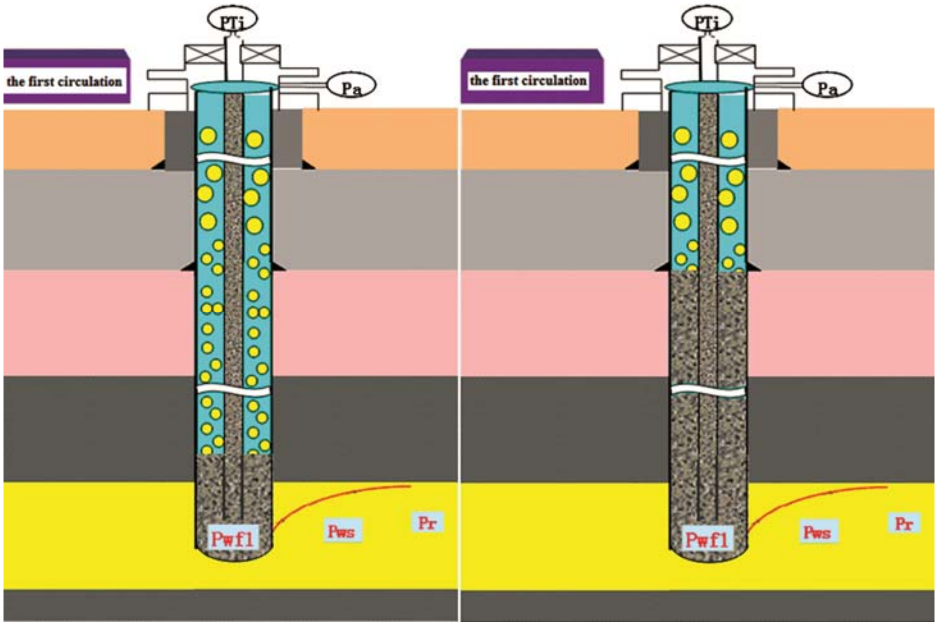
(1) The well kill operation

Taking the driller's method for example, during the first circulation, there is bubble flow in the mud when the original muds arrive at the drill bit and the bottom hole pressure increases due to the adjusted throttle valve. The gas influx rate decreases and the polluted mud are out of the wellbore, shown in Figure 1.

In the second circulation, there is no gas in the wellbore and the muds used are heavier than the original muds, as showing in Figure 2.

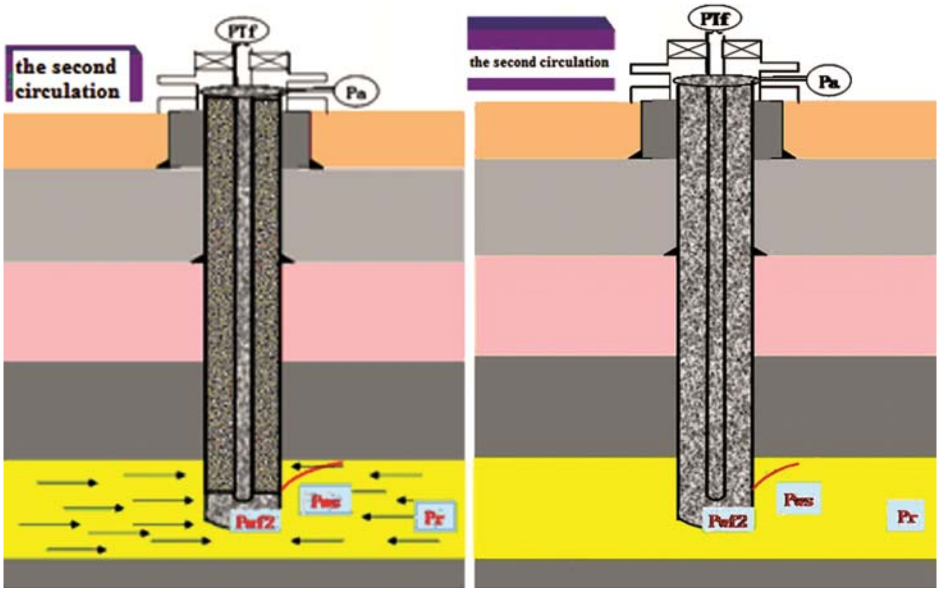
(2) The casing and tubing pressure curve characteristics during well killing

In the first circulation, the original muds are pumped into the wellbore and pull the influx gas out. The casing pressure increases when the influx gas rises along the wellbore and will reach to the peak. After that, the gas will be circulated out of the wellbore gradually. Then the casing pressure will reduce and be equal to the shut-in standing pressure finally. In the second circulation, the heavier muds instead of the original are pumped. Before the heavier muds reach at the drill bit, the casing pressure will be constant. The standing pressure reduces to P_{tf} and keeps to be constant. When it is circulated to the wellhead, the hydraulic pressure of muds is balanced with the bottom hole pressure. The casing pressure reduces to 0, which is the successful sign of the driller's method. The key point is that the bottom hole pressure is always larger than the formation pressure, as shown in Figure 3.



(a) the muds arrive at the drill bit ($P_{wf1}>P_r$, $P_{Ti} = P_{sp}+ \Delta P_{ci}$) **(b) the muds are pulled into the annular ($P_{wf1}>P_r$, $P_{Ti} = P_{sp}+ \Delta P_{ci}$)**

Fig. 1 — The first circulation of driller's method



(a) the heavier muds arrive at the drill bit **(b) the annular is filled with the heavier muds**

Fig. 2 — The second circulation of driller's method

The curve characteristics of well killing failure

(1) The failure due to the underground blowout

The underground blowout includes: uper layer blowout and lower layer leak, upper layer leak and lower layer blowout, the blowout and leaks occurs in the same layer. According to these conditions, the well killing parameters are different:

A. The upper layer blowout and the lower layer leak

It is associated with the blowout rate of the upper high pressure layer. Assuming the rate is high, there will be parts of fluid leaking into the formation and parts flowing to the surface. The frictional pressure drop increases with the rising velocity in annular when the opening of throttle valve remains to be

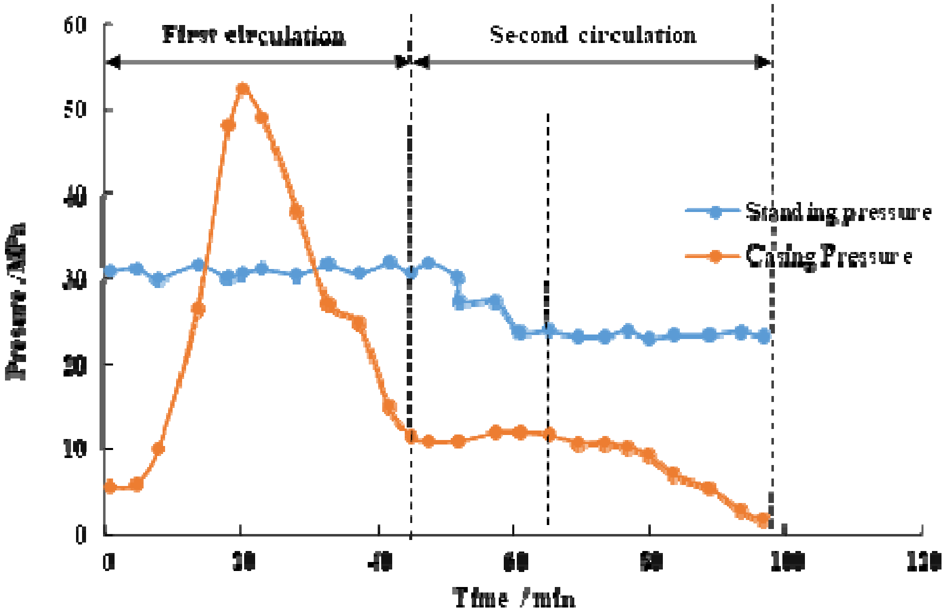


Fig. 3 — The successful well kill curve in some well of Puguang gas reservoir

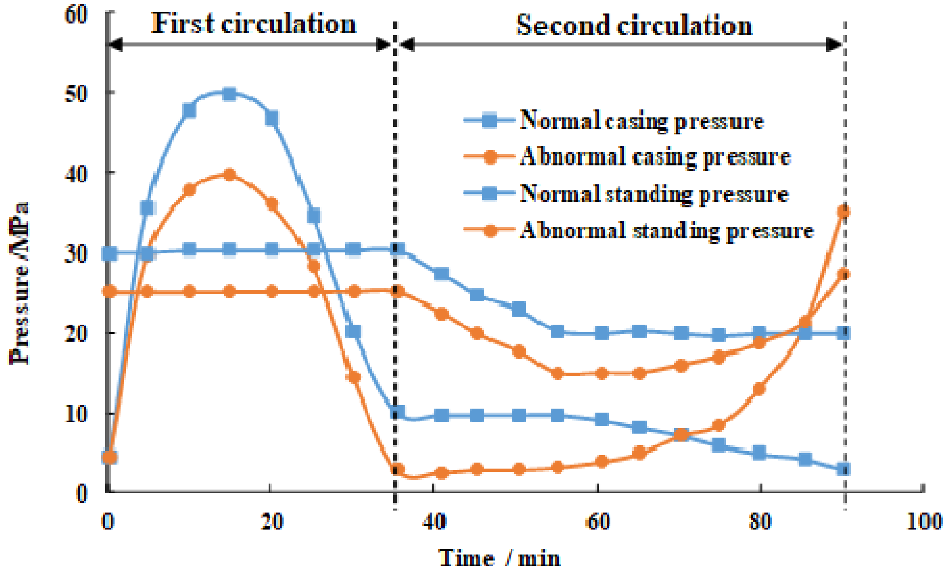


Fig. 4 — The casing and standing pressure curves when the influx rate is high

constant. The casing and standing pressure will increase, seen in Figure 4. Assuming the rate is low, the fluid will all flow into the lower layer and parts of the muds will flow into the leak layer. The rising velocity in the annular will decrease when the opening is constant. And the casing and standing pressure will reduce.

B. The upper layer leak and the lower layer blowout

This situation is same to the part A.

C. The blowout and leak happens in the same layer

This situation happens in the layer of which the permeability is good, the fracture and caves are developped. The casing and standing pressure will increase when blowout happens and will decrease when leaks happen.

(2) The failure due to the failure of well control equipment on the surface

A. The throttle valve failure

When the throttle valve is failure, the casing pressure in the well head will be incontrolable and the well can't be killed according the casing pressure. Taking the driller's method for example, one is the failure in the first circulation and the other is the failure in second circulation.

In the circulation, the casing pressure can't be increased which results in that the bottom bole pressure is lower than the formation pressure and the well kill is failed. The throttle failure level can be reflected by the casing pressure. The casing pressure is lower, the failure is heavier, shown in Figure 5.

B. The surface casing failure

One of the failure is that the casing is good but the pressure bearing capacity is not high enough. The other is that the casing is broken. The first will be discussed here in detail. The casing pressure will not increase when it is equal to the bearing pressure. According to the "U" pipe theory, the bottom hole pressure will be lower than the formation pressure leading to that the gas will leak into the wellbore annuli and the well kill will be failure, seen in Figure 6.

The method for recognizing the failure of well killing early

The variance is used to represent the deviation between the random variables and mathematical

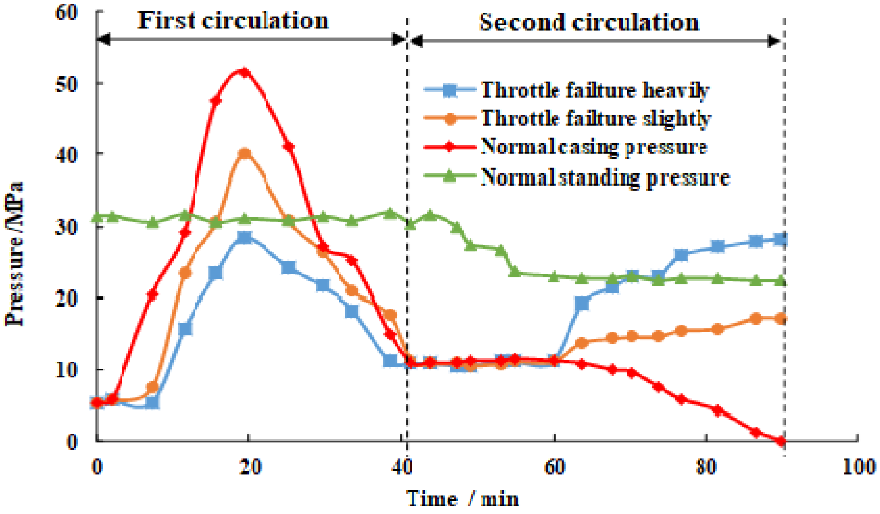


Fig. 5 — The casing and standing pressure curves in the circulation due to the throttle valve failure

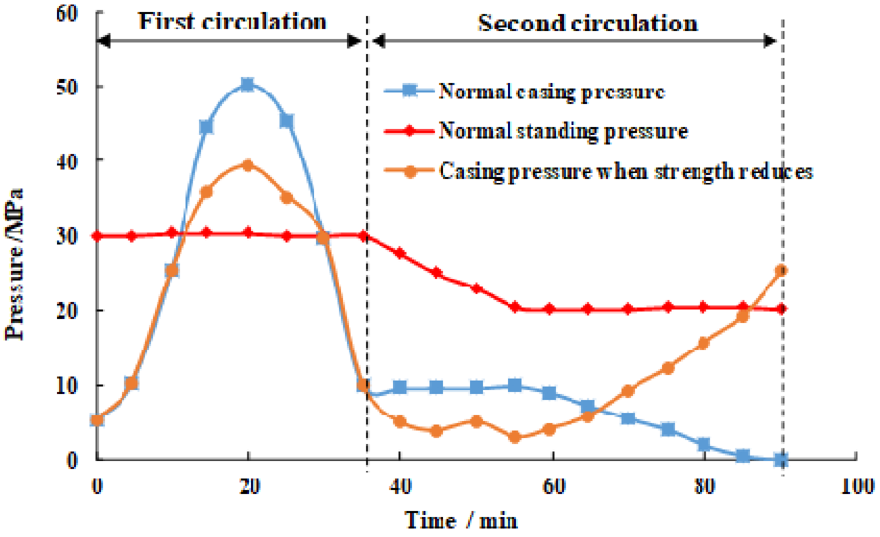


Fig. 6 — The casing and standing pressure curves when the surface casing bearing pressure is small

expectation in probability and mathematical statistics theory[15]. It is introduced into recognizing the failure early. The average value is the designed well killing parameter associated with Δt. Then the variance between the real well killing parameter and the designed parameter will be calculated. The deviation curve will be used for recognizing the failure of well kill early.

$$\sigma^2 = \frac{\sum_{i=1}^{n}(s_i - \bar{s})^2}{n} \quad \ldots (4)$$

where σ is the variance; $\bar{s}$ is the average value of the parameter designed; s_i is real well kill parameter.

The failure probability and development tendency of well killing can be evaluated and predicted by the probabilistic method and the covariance processing method. The failure can be recognized before the completion of first circulation based on this method. The opening of throttle value and the well killing parameter can be adjusted in time. According to the variance analysis, the failure will be worse after the casing pressure reaches to the peak, and the well killing parameter can be adjusted before this moment to avoid the failure, as shown in Figure 7.

The reason of blowout after the well killing failure

(1) The density of muds is too small to balance the formation pressure

After the well killing failure, it is difficult to predict the formation pressure accurately and calculate the mud's density. So the influx gas is flowing into the wellbore annuli during the well killing. When it is near the wellhead, the gas will expand strongly and the blowout will happen.

(2) The displacement of muds is too few to balance the formation pressure

The standing pressure should be recorded according to different pump stroke. Low pump stroke test should be taken before the well killing to ensure the displacement will be selected accurately when the throttles are adjusted. The improper displacement will result in the formation leak and the muds flowing into the formation. The blowout will happen when the formation pressure is underbalanced.

(3) The well kill parameters are not correct enough to balance the formation pressure

The throttle is adjusted to control the backpressure to ensure that the annular pressure is larger than the bottom hole pressure in the well killing. Then the influx gas will not flow into the wellbore. However the backpressure will be controlled imprecisely due to the throttle failure or the improper operations. The formation pressure will be larger than the annular pressure. The influx gas flows into the wellbore continually and the well killing will be failing. The blowout will happen finally.

The evaluation method for probability of blowout

Estimating the probability of blowout according to the shut-in pressure

The probability of blowout can be estimated by the shut-in pressure when the influx happens. The influx

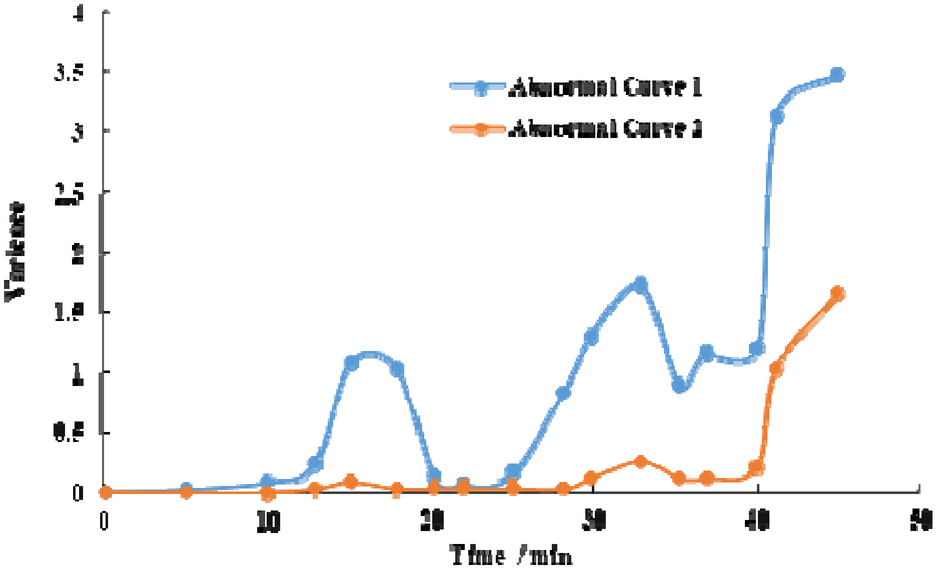


Fig. 7 — The variance analysis of well kill

level is associated with the porosity, the permeability and the negative pressure difference. These values are larger, the influx is more serious, the shut-in pressure is higher and the well killing is more difficult. The probability can be evaluated by the difficult degree and evaluation module of well control, shown in Figure 8.

(1) The module establishment

There will be one "evaluation point" in the module. The pressure of this point represents the underbalance degree in the well bottom and the largest shut-in well head pressure. So some pressure lines are needed to distinguish the pressure level. The slope of the line between the initial recovery point and the evaluation point represents the shut-in pressure recovery speed due to the gas influx capacity, refecting the formation factor. Some lines of different slope are needed to distinguish the formation factor level. Therefore, there are several horizontal lines and oblique lines in the module.

These lines are horizontal to define the amplitude of the shut-in pressure evaluation point. The boundary line between the low and middle pressure is 4 MPa and between the middle and high pressure is 10 MPa. The slope angle of boundary line between the low and middle formation factor is 25° and between the middle and high formation factor is 50° for defining the pressure recovery speed.

The relationships among the underbalance degree, the formation factor and the well control difficulty in Figure 8 are as follows:

- Area A: low pressure and low formation factor, well can be controled.
- Area B: low pressure and middle formation factor, well can be controled.
- Area C: low pressure and high formation factor, well control will have failed risks.
- Area D: middle pressure and low formation factor, well can be controled.
- Area E: middle pressure and middle formation factor, well control will have failed risks.
- Area F: middle pressure and high formation factor, the well control risk and difficulty will be high.
- Area G: high pressure and low formation factor, well control will have failed risks.
- Area H: high pressure and middle formation factor, the well control risk will be higher and difficulty will be high.
- Area I: high pressure and high formation factor, the well control failed risk and difficulty will be higher.

The boundary of pressure and formation factor should be adjusted according to the actual formation property.

(2) Elevating the well control difficulty based on the shut-in pressure recovery curve

The shut-in pressure recovery curve is affected by the underbalance degree and formation parameters. The formation pressure gradient, pressure gradient of

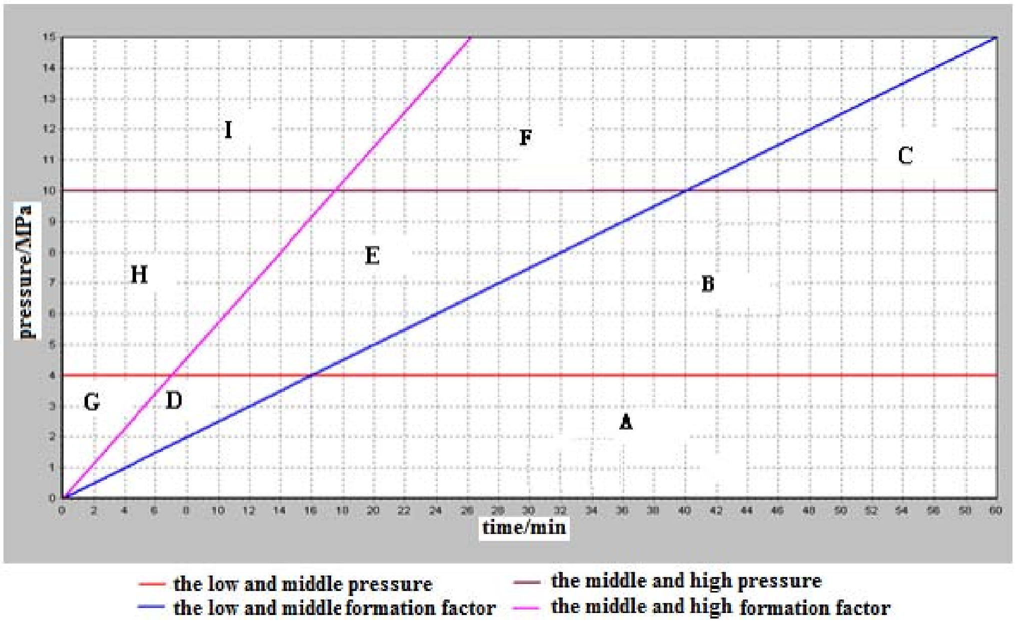


Fig. 8 — The difficult degree evaluation module of well control

drilling fluids and the drilling formation thickness affected by the drill rate and drill time will have an influence on the underbalance degree. The thickness is greater, the degree will be bigger in the same pressure gradient. Taking three group parameters in Table 1 for example, the pressure curves changing with time are shown in Figure 9.

It can be seen from Figure 9 that the pressure of the evaluation point represents the under balance degree, which is to say that the product of the well depth and the difference between formation pressure gradient and pressure gradient of drilling fluids. The slope of this point is the ration of maximum shut-in wellhead pressure and the recovery time, reflecting the recovery speed. It’s the product of the permeability and the drilling formation thickness. The well control difficulty of test 1, test 2 and test 3 is large, middle and low according the location of point A, B and C in the module.

(3) The well control difficulty can be analyzed by the module. The shut-in pressure recovery speed affects the well control. But there are two points to be noticed in the well drilling.

First, the drilling formation permeability will be unpredictable. The vertical permeability in the same formation will be different. The well control difficulty is uncontrollable once the influx happens.

Second, the effective formation thickness increases with the drilling formation thickness and it’s controllable.

The well control difficulty of different formation properties can be analyzed through the line slope of the evaluation point and the original point. Taking one well for example, the depth is 3500 m, the formation pressure gradient is 1.3 MPa/100 m, the muds density are 1.05 g/cm^3, one groups of permeability are 10 md, 100 md, 2000 md and one groups of drilling formation thickness are 1 m, 2 m, 4 m, 8 m. The calculation results are shown in Figure 10.

From Figure 10, it can be seen that the line slope increases with the permeability. The formation permeability is larger, the well control is more difficult with the thickness. Therefore, the well must be controlled early when the influx happens for the high permeability formation.

Table 1 — The data and results of shut-in pressure recovery test

Test	Well depth /m	permeability /md	Formation pressure gradient /(MPa/100m)	Muds density /(g/cm^3)	Drill rate /(m/hr)	Drill time /h	Well Control difficulty
1	4100	800	1.35	1.08	2	0.89	high
2	3300	120	1.25	1.04	2.5	0.76	middle
3	2500	40	1.27	1.15	2	0.53	low

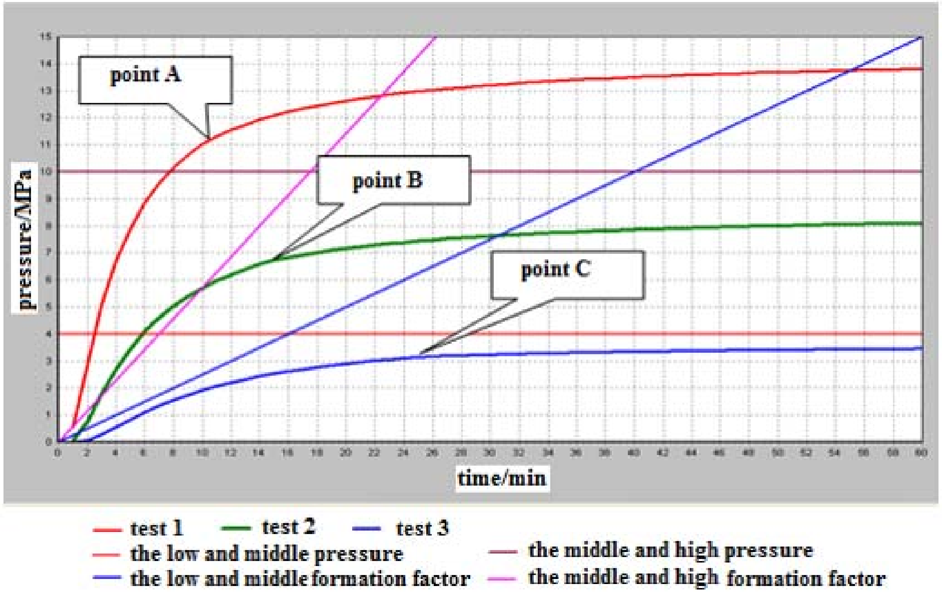


Fig. 9 — The well control difficulty elevated curves based on the shut-in pressure recovery curve

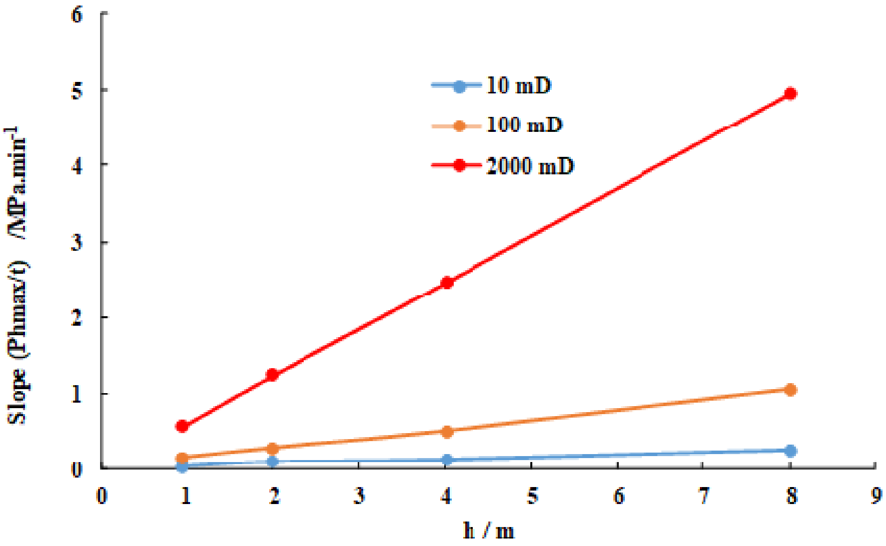


Fig. 10 — The effect of thickness on the well control difficulty in different permeabilities

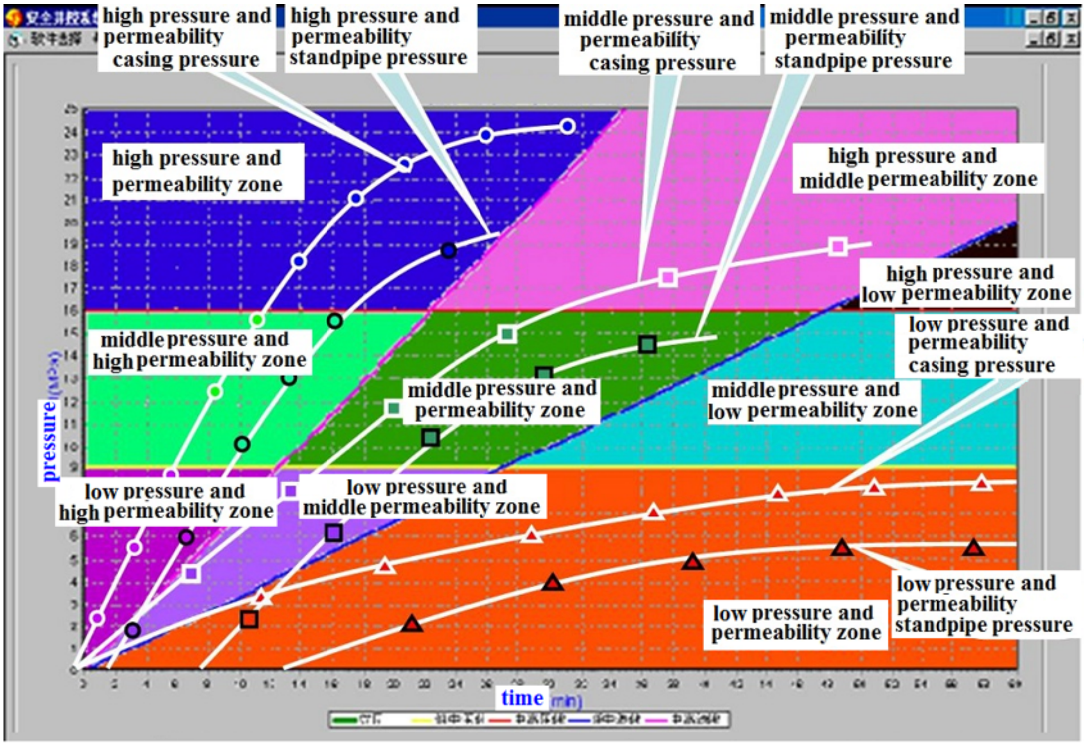


Fig. 11 — The template of influx formation permeability, pressure character and well bottom underbalance

(4) The shut-in pressure build-up template is established, as seen in Figure 11. The formation factor and under balance degree can be calculated based on this template. The evaluation point position of the shut-in pressure build-up is upper in the template, the underbalanced degree is larger. The slope of line connecting between the evaluation point and initial point is larger, the formation factor is larger. The difficulty of well control will be larger. There are several curve groups about the standing pressure and the casing pressure curve. The formation pressure can be calculated according to the curve groups. The shut-in pressure build-up zone is divided into 9 areas which represent

different difference between the well bottom pressure and the formation pressure.

As shown in Figure 11, there will be more influx gas in the annular if the distance between the shut-in standing pressure and the shut-in casing pressure is larger. If they locate at the left upper of Figure 11, the pressure and permeability of the formation is high. If they locate at the right lower of Figure 11, the pressure and permeability of the formation is low. The well killing risk can be roughly evaluated according this template.

Estimating the probability of blowout according to the changes of casing and standing pressure

The changes of casing pressure can represent the varying annular transient pressure and the influx gas rising in wellbore annular. It will increase during circulation. But it will reduce when the gas arrives at the well head and be equal to the shut-in standpipe pressure. If the casing pressure increases all the time and reaches the pressure bear limit of the well head equipment, it is needed to open the relief line, which is to say the gas influx still happens and the probability of blowout is larger.

The four hardware systems and one evaluation system for decreasing or avoiding the properbility of blowout

The well control out of control is a disastrous accident in the drilling engineering. Preventing out of control means there will be no disastrous accident.

(1) The blowout out of control factors

A. BOP failure

The different types of BOP have different bearing pressure. If the bearing pressure is lower than the pressure needed, the well will not be shut in, which means the BOP is failure and the blowout will happen.

B. The throttle and relief equipment failure

The throttle and relief equipments are not paid enough attention for checking or testing on time. The blowout happens if the throttle equipment are failure.

C. Well control equipments are failure

The standing pressure is affected by the well control associated equipment. The standing pressure is controlled by the pump and the drilling pipe strength. If the well bottom hole pressure can't be increased by the drill pipe or killing pipe, which means the pumped muds can't reach to the well bottom. Then the well control equipment will be in failure and the well control out of control will happen.

D. The integrity of the wellbore hydraulic

The integrity includes: the wellbore design, such as casing inner pressure resistance, drilling pipe outer pressure resistance and the fracture pressure at the casing shoes. If one of them don't match with the formation pressure, the well control will be out of control.

(2) The four hardware systems for decreasing or avoiding the risk due to the well killing failure

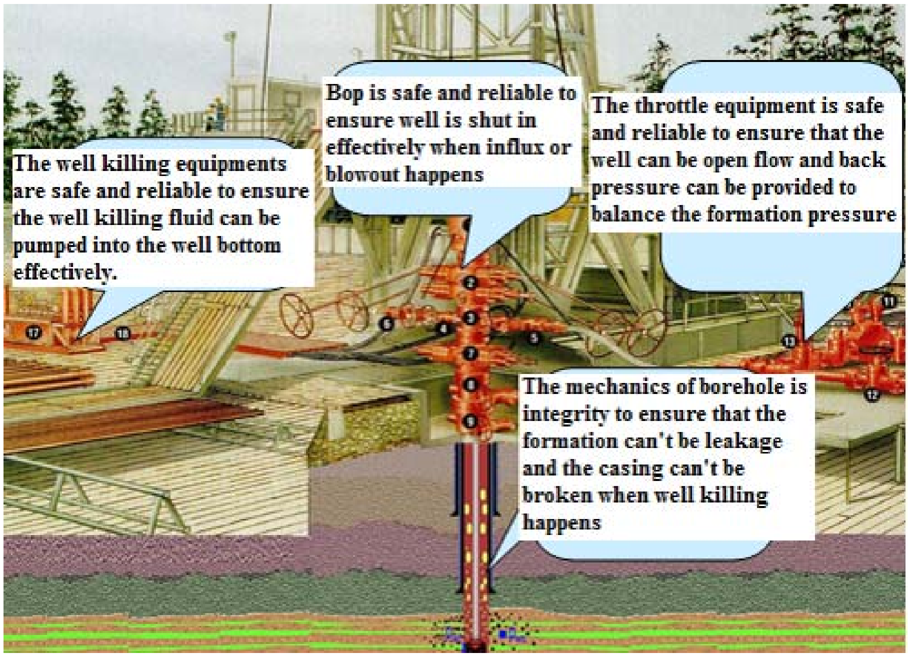


Fig. 12 — The four hardware systems in well control

A. Ensure the BOP is safe and reliable.

B. Ensure the throttle associated equipment are safe and reliable.

C. Ensure the well control associated equipment are safe and reliable.

D. Ensure the wellbore hydraulic is integrity.

(3) The evaluation system for decreasing or avoiding the risk due to the well killing failure.

This system can ensure the four hardware systems safe and reliable, shown in Figure 12. If the four hardware systems are safe and reliable before the well killing and not be reliable due to the operation methods, this system will evaluate and adjust the operation.

Conclusion

(1) Based on the two-phase gas-liquid flow, the characteristics of curves before and after well killing failure are analyzed.

(2) The method for recognizing the failure of well killing early is established based on analyzing the abnormal curve bahavoirs between the real well killing and the ideal parameters. The failure probability and development tendency of well killing can be evaluated by the probabilistic and the covariance processing method.

(3) The shut-in pressure build-up template is established. The evaluation point position of the shut-in pressure build-up is upper in the template, the underbalance degree is larger. The slope of line connecting between the evaluation point and initial point is larger, the formation factor is larger, and the difficulty of well control will be larger.

(4) The four hardware systems and one evaluation system are recommended for decreasing or avoiding the risk due to well killing failure. It provides a theoretical guidance to the well control of the offshore oil and gas wells, significantly for the development of oil and gas wells, which will be more scientific, safe and efficient .

Acknowledgement

This paper was sponsored by the National Natural Science Foundation of China (51504279), National key research and development program of china (2017YFC0307604), the Fundamental Research Funds for the Central Universities (17CX02073), 973 Project (2015CB251200) and the Construction Project of Taishan Scholars. We recognize the support of China University of Petroleum (East China) for the permission to publish this paper.

References

1 "WA oil spill 'one of Australia's worst'", ABC News, (2009).

2 Deepwater Horizon Marine Casualty Investigation Report (PDF) (Report), Office of the Maritime Administrator, (2011).

3 F_129, "China needs zero tolerance for concealing major accidents - People's Daily Online", English. peopledaily.com.cn., (2011).

4 M. Enamul Hossain, Abdulaziz Abdullah Al-Majed, Fundamentals of Sustainable Drilling Engineering, New Jersey: John Wiley & Sons, Inc, (2015). 32-53

5 Grace R D, Blowout and well control handbook, Gulf Professional Publishing, (2017). 64-75

6 Sule I, Khan F, Butt S, et al, Kick control reliability analysis of managed pressure drilling operation, *J. Loss Preven. Process Indus*., 52(2018)7-20.

7 F. Aarsnes U.J., Ambrus A, Vajargah A.K, et al, A simplified gas-liquid flow model for kick mitigation and control during drilling operations, Proceedings of the ASME 2015 Dynamic Systems and Control Conference, Columbus, Ohio, USA, (2015).

8 Sun X.H., Sun B.J., Zhang S, et al, A new pattern recognition model for gas kick diagnosis in deepwater drilling, *J. Petrol. Sci. Eng.*, 167(2018) 418-425.

9 Wang N, Wang J.B, Sun B.J, et al, Study of transient responses in the APWD measurements during gas influx, J. *Nat. Gas Sci. Engg*., 35(2016)522-531.

10 Oliveira F F, Sodré C H, Marinho J L G, Numerical investigation of non-Newtonian drilling fluids during the occurrence of a gas kick in a petroleum reservoir, *Brazilian J. Chem. Engg*., 33(2)(2016)297-305.

11 James P. Brill, Hemanta Mukheejee, Multiphase Flow in Wells, Society of Petroleum Engineers, (1999)28-67.

12 Kabir C.S. and Hasan A.R., Determining Circulating Fluid Temperature in Drilling, Workover, and Well-Control Operations, SPE Annual Technical Conference & Exhibition held in Washington, DC, (1992).

13 Yin B.T, Liu G, Li X.F, Multiphase Transient Flow Model in Wellbore Annuli during Gas Kick in Deepwater Drilling based on Oil-based Mud. *Appl. Math. Modell*., 51(2017) 159-198.

14 Yin B.T, Li X.F., Sun B.J., et al, Hydraulic Model of Steady State Multiphase Flow in Wellbore Annuli, *Petrol. Explor. Dev*., 41(3)(2014)399-407.

15 Bronshtein I.N., Semendyayev K.A., Musiol G., Mühlig H. *Probability Theory and Mathematical Statistics*. In: Handbook of Mathematics. Berlin, Heidelberg: Springer, (2015). 87-99