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Determining the difference of kick tolerance with single bubble and dynamic multiphase models: Evaluation of well-control with water/synthetic based muds

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ABSTRACT

Determining the magnitude of an influx into the wellbore when a kick event occurs is very important during well design as well as the well execution phases. This research is conducted to determine the kick tolerance where the single bubble phase model is applied and also to compare it with the dynamic multiphase model. The information on the well and the parameters used are taken from the high pressure and high temperature well drilled in Malaysia. Dynamic multiphase modelling is capable of supporting more kick volume compared to single bubble gas phase modelling where it considers multiple fluid phase in an influx and applies the gas characteristic to have a multiphase pressure loss. Dynamic multiphase gives more kick tolerance to fracture the weakest point at the casing shoe where single bubble gas phase is more conservative when it allows influx. The effect of pore pressure, mud weight, mud type, oil composition in mud, as well as the circulation kill rate are explored in dynamic multiphase. Increasing the mud weight in either case reduces the maximum allowable kick volume of an influx due to the reduction in MAASP between fracture pressure and hydrostatic pressure at the casing shoe. Higher kick volume can be achieved using WBM compared to SBM. In addition, a sensitivity analysis is performed from the dynamic multiphase simulations to analyze the impact on the kick tolerance during the increase in mud weight as well as the pore pressure uncertainties. Moreover, the impact of kick tolerance has been investigated when different types of mud are used, such as water-based mud and synthetic-based mud. Based on the accuracy of the presented procedure, the prediction of kick tolerance from dynamic multiphase modelling can be used as a guideline to identify the behavior of an influx when a kick event occurs.

1. Introduction

Kick tolerance is one of the aspects to consider when designing a well for the optimization of the casing setting depth and also when controlling the well when an influx enters the open hole in the wellbore and safely circulate the influx out to the surface. To determine the kick tolerance for each section of the hole to be drilled, the single bubble gas phase model is widely used in industry. However, the accuracy of the kick tolerance is a challenge because the calculation method only considers the single bubble gas and does not take into account the gas influx and migration characteristic. Additionally, there is no accepted standard method in calculating kick tolerance for the drilling industry where neither unconformity nor consistency is compared. High pressure high temperature (HPHT) wells are technically complex and present a high risk during design and execution. This gives a lower margin of error and the consequences of failure have a significant impact on the drilling operation in terms of cost. One of the factor that make HPHT wells more difficult than conventional wells is that they have a narrow operating window between pore pressure and fracture pressure, which can be a big problem in the well

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control operation. Since drilling into a narrow margin window in an HPHT environment provides a lower safety factor, an accurate and absolute kick tolerance is desired. Thus, an alternative method is performed for the dynamic investigation of kick which taken into account the dispersion, migration, expansion, and solvent of the gas. Temperature, mud properties, reservoir, wellbore geometry, and drilling operation are taken into account as these factors could have a significant impact on dynamic kick tolerance. Therefore, the aim of this paper is to conduct a numerical study on the kick tolerance for single bubble gas and the dynamic multiphase effect and compare them to check for differences that could have a significant impact on the design of HPHT wells and the drilling operation. In addition, the impact of the composition of the oil in the synthetic based mud (SBM) as well as the dynamic of circulation kill are also evaluated.

2. Background

In deep water drilling, the accurate determination of the behavior of the two-phase gas–liquid flow of the wellbore is important for the well control treatment. A study shows that without taking into account the effect of gas solubility, the bottom hole pressure could be overestimated by 3.2% (3.74 MPa) while it could be underestimated by 4.2% (2.92 MPa). Moreover, the bottom-hole pressure could be overestimated by 11.4% (7.94 MPa) under constant flow conditions without taking into account the effect of heat transfer [1]. When the bubble–bubble interaction and mass transfer are not taken into account, the bottom-hole pressure is underestimated and the free gas fraction and overflow rate are overestimated. But, the impact of heat transfer is opposite on the behavior of two-phase flow [2]. An ensemble classifier based on a Kalman Unscented Filter (UKF) can identify drilling defects with 93% accuracy regardless of the influence of pressure and temperature [3].

Accurate thermodynamic properties of fluids with as a function of temperature and pressure are essential to estimate the dynamics of the gas blow scenario in the well [4]. In the past, extensive research on estimating kick tolerance, risk assessment of blowout preventer, smooth drilling and surface facilities have been carried out [5–38]. A study also quantified the blowout flat time in the well control operation [39]. Recently, machine learning approaches have also been used for safe well operations [18,40–43]. Similarly, the subject such as kick volume/kick tolerance needs attention to construct a safe wellbore. When calculating the kick tolerance, annular friction pressure drops are often entirely neglected as they are considered minor or considered an additional safety factor [44]. Early detection of the kick plays a critical role in Managed Pressure Drilling (MPD), where the volume of the kick tolerance is critical. One study discussed the impact of environmental variables for gas kick and the different methods of systematically kick detection [45]. However, there is considerable uncertainty involved in the kick warning sign in terms of geological nature, reservoir type, drilling orientation and depth. In the case of any drilling operation, the response to the kick should be indicated appropriately depending on the intensity of the kick and the rate of propagation along the wellbore.

The pressure difference in the casing of the maximum slip single bubble model and the non-slip dispersed flow was found to be considerable, especially at lower background pressure values [46]. The findings with the single bubble model show that some components have more influence than others and that the value is not constantly in the same direction. In addition, the impact on deep water wells is more intense due to the long choke line. Thus, simplification and generalization of the calculation of the kick tolerance in well design is not possible [47]. The main objective of this research is to calculate the significant difference in kick tolerance between single bubble gas phase and the dynamic multiphase simulation in HPHT. Various gas behaviors were included such as migration, expansion, dilution, dispersion and evaluated their effect on gas behavior/kick volume in a well. This paper explored the significant differences between kick tolerance in the single bubble gas phase and dynamic multiphase at pore pressure uncertainty in the narrow operating window of HPHT wells. Moreover, this study includes the impact of changing mud weight on kick tolerance. Also the effect of gas characteristic on kick tolerance. Finally, the sensitivity analysis is presented for the different types of mud used, the properties of mud based on oil composition and kill circulation rate which will affect the kick tolerance value in dynamic multiphase.

3. Theory and kick tolerence modelling

In this section, the procedure for calculating the kick influx volume is presented. The kick volume is determined based on the Well information and the equations presented in the kick tolerance calculation. Well data information includes well type (HPHT), depth (target depth and last casing depth), formation, mud and, hole geometry. The main activities involve the determination of the kick tolerance for the single bubble gas phase, the dynamic multiphase model and sensitivity analysis.

3.1. Kick

A kick can be defined as an unwanted influx or formation fluid flowing into the well. Based on the upstream activities, the kick is an influx of wellbore fluid into the wellbore and a possible loss of primary well control which must be controlled by secondary control (BOP)[48]. A kick can occur under three conditions such as kick while drilling, kick while tripping out (referring to swabbed kick), and kick while out of hole (drill pipe out of hole). The main causes of kick are due to the hydrostatic pressure underbalance inside the wellbore which has occurred due to i. Reduction in hydrostatic pressure (Pressure = Density of mud, pgg $\times$ 0.052 $\times$ Vertical depth, ft). Based on the hydrostatic pressure formula given above, the reduction in hydrostatic pressure is mainly caused by the drop in the level of mud in the hole, the drop in the density of the mud and the low density of the formation fluid entering the well bore [49]. A drop in the level of mud in the hole can occur when there is a loss of circulation at the bottom of the hole where the hydrostatic pressure exerted by the density of the mud exceeds the formation strength and breaks the formation. As the formation starts to break, the mud inside the wellbore will flow into the formation. Mud density drop in mud column may occur due to dilution by water or base oil, removal or settling of barite at the bottom of the hole, pumping of lightweight pills or whole mud, cleaning hole cuttings and cementing pipes. A low density of formation fluid entering the wellbore may be due to the gas cut mud and swabbing where the density of the mud at the down-hole is not sufficient to prevent the formation fluid from entering the wellbore. When the formation fluid is lighter than mud, it will reduce the hydrostatic pressure at the down-hole. ii. Increased pressure of the formation fluid (abnormal pressure) [49]. The main causes of abnormal pressure are under-compaction in shale, salt beds, mineralization, tectonic causes, faulting, diapirism and reservoir structure [50].

3.2. Swabbed kick

Swabbing occurs when the bottom hole pressure is reduced below the formation pressure due to the pulling effect on the drill string, allowoing an influx of formation fluids to enter the wellbore

[50]. How did this happen, because when pulling out of the hole, the narrow clearance between the bit and the hole can create a suction like effect that reduces the hydrostatic head for a short period of time. Most of the time this happens when pulling out drill pipe from the hole without filling it with the mud to replace the displacement of the removed pipe. Therefore, tripping is normally carried out with hydrostatic mud which overbalance the pressure of formation fluid, where this safety margin maintains well control [49]. Several studies have been carried out to investigate the impact of water based and synthetic based muds [51–54]. Factor affecting the swabbing are the pulling speed of the drill-pipe, mud properties, viscosity and hole geometry [50].

3.3. Kick tolerance

Although kick tolerance is a critical and fundamental concept for the drilling industry, there are no standards used by operators and contractors. Various definitions of kick tolerance have been controversial and introduce in the industry in terms of pit gain, mud weight increase, or underbalance pressure [47]. The kick volume can be defined as follows; i. The maximum allowable pore pressure, in equivalent mud weight, if a kick with a certain influx volume occurs at a particular depth with a specific drilling fluid, the well may have able to shut-in and circulate kick out safely without fracturing casing shoe. ii. The maximum increase in mud weight allowed by the casing shoe pressure integrity test with no influx into the wellbore (referring to the formation integrity test, FIT and leak- off test, LOT). iii. The ability of the wellbore to withstand the state pressure generated during well control operations without fracturing the weakest formation. iv. The maximum influx height that the section of the open hole section can tolerate without fracturing the formation. This influx height is then converted to a volume based on the cross section and geometry between the wellbore and the drill string. Derived volume is defined as the limited kick tolerance in terms of barrels. v. The largest influx volume that can be safely removed from the well based on the LOT or FIT result. This is the measure of the risk of the well control when drilling the section of the hole. Table 1 shows different hole sizes and respective kick volumes.

There are two important factors to use in determining kick tolerance, namely the kick intensity and kick volume. The calculation of this factor has been discussed in detail in the Sections 3.13 and 3.14.

3.4. Kick intensity

The intensity of the kick is a underbalance magnitude of hydrostatic pressure or the amount of overpressure that has entered from the formation flow into the well. It can also be defined as the difference between the maximum anticipated formation pressure and the planned mud weight and is expressed in the same units as the mud weight, ppg [55]. For now, if the mud density is 10 ppg and the kick intensity is 0.5 ppg, then the equivalent pore pressure of the kick formation is the addition of the both values, which in this case is 10.5 ppg.

$$P_f - MW = KI \tag{1}$$

whereKI is kick intensity, ppg; P_f is formation pressure, ppg; MW is mud weight, ppg

Table 1
Typical value of kick volume.

Hole Size (inch)	Kick Volume (bbl)
12.25″ and above	50
8.5″	25
6″ and smaller	Full Evacuation

The intensity of the kick is an important and key parameter to assume that reflects the pore pressure to be used when calculating the kick tolerance. There is confusion in the definition of the hypothetical pore pressure of the kick zone (called as "worst case pore pressure"). The first method is to refer to "predicted pore pressure + kick intensity" as the pore pressure of the kick zone. While the second method is by referring the "mud weight use + kick intensity" as the kick zone pore pressure. Such "mud weight use + kick intensity" method is used to quantify the kick zone pore pressure [55]. For a swabbed kick, the kick intensity is assumed as zero (0), where mud weight is overbalance and above the formation pressure. When a swabbed kick is occurred, the suction taking the influx with a formation pressure at bottom hole into the wellbore.

3.5. Kick volume

Kick volume is the measure to quantify the influx that entered the wellbore from the formation. There are many type of influx, but the influx of gas is still used for the well control calculation due to the expansion effect and reflects the worst case scenario. The required influx volume at the required kick intensity for the well to circulate out safely should be a realistic value that the drilling crew can detect the influx and close in the well on the rig [56]. Table 2 shows the type of influx and quantification of the respective influx gradient.

The influx volume is calculated based on the multiplication of the calculated influx height over the cross section of the area between the wellbore and the drill string. However, on the rig, normally this influx volume is detected based on the volume of mud pit gain. The detail of this calculation will be discussed later in the section on the calculation of the kick tolerance.

$$V_{influx} = H_{influx} \times Ann.Cap \tag{2}$$

where V_{influx} is the volume of influx, bbl; H_{influx} is the height of influx, ft; $Ann.Cap$ is the annular capacity between wellbore and drill string, bbl/ft

3.6. Maximum anticipated annular surface pressure

The Maximum Anticipated Annular Surface Pressure (MAASP) is defined as the maximum annular pressure that can be allowed to develop at the surface before the fracture pressure of the formation just below the casing shoe is exceeded. During the well control operation, it is important that the pressure exerted on the surface does not exceed the fracture gradient at this weakest point [50]. The formation fracture pressure was determined by the Leak-Off Test (LOT) carried out after the casing was set.

$$MAASP = P_{fracture@shoe} - HSP_{@shoe} \tag{3}$$

where $MAASP$ is the maximum allowable anticipated surface pressure, $P_{fracture@shoe}$ is the formation breakdown pressure at shoe, $HSP_{@shoe}$ is the hydrostatic pressure of mud.

3.7. Pore pressure and fracture pressure

Pore pressure is the pressure exerted by fluid trapped in the pore space of rock whereas fracture pressure is the pressure need

Table 2
Influx gradient evaluation guidelines [56].

Influx gradient (psi/ft)	Influx Type
0.05–0.2	Gas
0.2–0.4	Probable combination of gas, oil and/or salt water
0.4–0.5	Probable oil or salt water

to propagate a fracture away from the wellbore and cause loss of circulation [57]. In order to safely plan and drill a well, it is necessary to have some knowledge of the pore pressure and fracture pressure of formation to be encountered so that the borehole pressure is always between the pore pressure and fracture pressure. If the borehole pressure falls below the pore pressure, then an influx of the formation fluids from the pore space will flow into the wellbore. Whereas if the pressure of the borehole exceeds the fracture pressure, then the pressure will fracture the formation and the drilling fluid will flow to the formation [50].

3.8. Single bubble gas phase model

The calculation of the kick tolerance is based on the single bubble gas model where the model takes a single bubble gas of a certain volume flow rate in the well at the bottom of the hole and then calculate by height and volumes, and determines the maximum pressure at the shoe, the illustration of single gas bubble phase is presented in Fig. 1 (a). It then compares this pressure to the leak off test value. In the other hand is, to determine the height of influx based on the maximum anticipated annulus surface pressure (MAASP) which indicate the maximum pressure that a casing shoe can accept before it fracture. Then, the calculated height of influx is transform into volume inside the wellbore. For both method, an incremental of influx volume from bottom hole to top of casing shoe is been applied by using gas law (Boyle's Law) during kick circulation. The single bubble gas model is assume that the kick influx will occurred in a single phase gas and remains so as it is circulated up and out of the wellbore which neglect the dispersion, solution, expansion and migration of a gas characteristic as well as the temperature effect of an influx into the wellbore [58,59]. Besides that, this model also ignoring the mixture gas–liquid density and gas compressibility (z factor), where in the final calculation will always result in a conservative solution [60].

3.9. Single bubble gas phase kick tolerance calculation approach

The first step in the simplified calculation of the single bubble gas phase kick tolerance (constant temperature, constant density, no compressibility) is to define the maximum vertical height of a gas influx, H_{influx} at the casing shoe (assumed to be the weakest point in the open hole) based on fracture gradient, mud weight, kick fluid density, predicted pore pressure and maximum annulus allowable surface pressure (MAASP) [47]. The procedure for calculating the kick tolerance is presented. Based on the Fig. 1(b), the maximum annulus allowable surface pressure to fracture the formation at casing shoe is calculated by using following equations:

$$MAASP = P_{frac} - HSP_{@shoe}$$

$$= (0.052 \times \rho_{frac} \times CSD) - (0.052 \times \rho_{mud} \times CSD) \quad (4)$$

where the pressure equilibrium when the influx at casing shoe is apply:

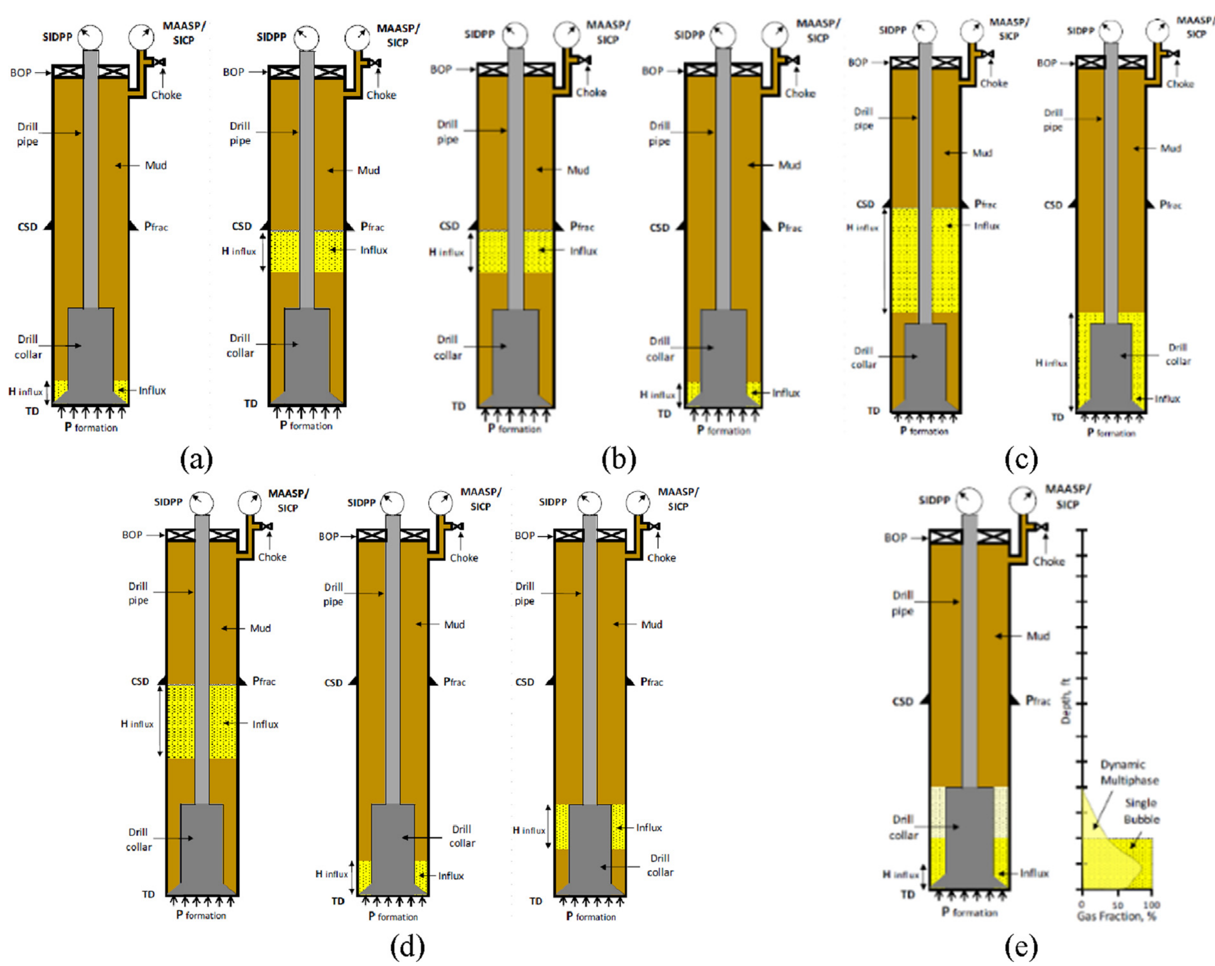


Fig. 1. Different Well illustrations. (a) Single bubble gas phase, (b) by taking a kick and expand at the shoe, (c) illustration when Height Influx > BHA Length, (d) illustration when Height Influx < BHA Length, (e) Comparison of single bubble and dynamic multiphase in well schematic.

$$P_{formation} = MAASP + HSP_{@shoe} + P_{influx} \times HSP_{@belowinflux} + 0.052 \times \rho_f \times TD$$

$$= MAASP + (0.052 \times \rho_{mud} \times CSD) + (0.052 \times \rho_{influx} \times H_{influx}) + 0.052 \times \rho_{mud} \times ((TD - CSD - H_{influx})) \quad (5)$$

Here, the height of influx at shoe (critical height before fracture the shoe) can be calculated as:

$$H_{influx} = \frac{MAASP - (0.052 \times TD \times (\rho_f - \rho_{mud}))}{0.052 \times (\rho_{mud} - \rho_{influx}} \quad (6)$$

Next, the volume of the influx at the casing shoe can be calculated by multiplying the H_{influx} with annular capacity across the drill pipe:

$$V_{influx@shoe} = H_{influx} \times Cap_{annulusDP}$$

$$= H_{influx} \times \frac{d_{oh}^2 - d_{dp}^2}{1029.414} \quad (7)$$

Then, the influx at the shoe $V_{influx@shoe}$ is taken to the bottom to calculate the influx volume at bottom hole (V_1) by applying the Boyle's Law:

$$V_1 = \frac{V_{influx@shoe}}{P_{fracture}} \times P_{formation} \quad (8)$$

This is the total influx volume at the kick zone, which it will expand to the casing shoe, which will cause the shoe to pressure reach the maximum allowable pressure before it fracture (fracture pressure). However, it is important to note that the kick volume at bottom hole will vary with the BHA length and geometry before it reach the critical height influx at casing shoe. Therefore, a modified kick tolerance calculation should be applied to give an absolute kick volume so that the integrity of the casing shoe shall not be compromised [47]. The first condition for modified kick tolerance calculation is when the height of influx is greater than the BHA length (H_{influx} > BHA Length) as shown in Fig. 1 (c), then the height of influx has been taken to the bottom of hole and multiply it across the annulus capacity of drill collar and drill pipe.

$$V_{influx@DC} = H_{BHA} \times CAP_{annulusDC} \quad (9)$$

$$V_{influx@DP} = H_{influx} - H_{BHA}) \times CAP_{annulusDP} \quad (10)$$

$$V_2 = V_{influx@DC} + V_{influx@DP} \quad (11)$$

Then both calculated influx volume of V_1 and V_2 are compared and the smaller value has been taken as the total influx volume. Thus, due to smaller value will create a more conservative, hence safer kick tolerance [47]. The second condition for modified kick tolerance calculation is when the height of influx is lesser than the BHA length (H_{influx}<BHA Length) as shown in Fig. 1 (d), then the height of influx has been taken to the top of BHA and multiply it across the annulus capacity of BHA.

$$V_{influx@BHA} = H_{influx} \times Cap_{annulusDC} \quad (12)$$

Then, the influx at the shoe $V_{influx@BHA}$ is taken to the bottom to calculate the influx volume at bottom hole (V_3) by applying the Boyle's Law:

$$V_3 = \frac{V_{influx@BHA}}{P_{fracture}} \times P_{formation} \quad (13)$$

Then the two calculated influx volume of V_1 and V_3 are compared and the smallest value was taken as the total influx volume. This due to the smaller value will create a more conservative, hence safer, kick tolerance [47]. It is conceptually wrong to neglect the BHA length ifH_{influx} < BHA length, then the kick will most likely not be circulated out from the wellbore but it may create an unsafe event where the kick will fracture the shoe before reaching the shoe and induce losses [47].

3.10. Dynamic multiphase model

The dynamic multiphase model is an improved model based on the simplified kick tolerance of the single bubble gas where it takes into account the changes in gas–liquid properties in a wellbore system during a kick, an illustration of single bubble and dynamic multiphase is presented in Fig. 1 (e). The magnitude of the changes for these fluids depends on the well control event when a kick is taken, then follow by the standard well control procedure of shutting down the pumps and closing the BOP, then allowing the bottom hole pressure to be constants before circulating out the influx [59]. Due to this, it caused a multiple phase of fluids such gas and liquid to exist in a particular influx's properties which give a significant impact on the pressure gradient in wellbore system compared to the single bubble gas phase. It also take into account the characteristic of gas dispersion when mud circulation while drilling, gas migration and expansion when shut in and circulating influx out while holding constant bottom hole pressure, gas dissolving in oil based mud at downhole condition and coming out of solution when bubble point is reached at surface, and also the temperature effect of the formation and drilling fluids [48]. Besides that, variable properties such as hole geometry or annulus volume, reservoir permeability and porosity, the drawdown between reservoir pressure and hydrostatic pressure, circulation rate while taking a kick and also temperature effect at downhole and surface will also give a significant impact to the dynamic multiphase kick tolerance calculation [48]. Instead of only applying single bubble gas phase for kick tolerance model, in the dynamic multiphase model, the multiphase pressure loss model has been applied to determine the changes of pressure gradient of a kick in a wellbore which is different to single bubble gas model. As for the next section, a short study on multiphase pressure loss model has been presented to give a simple explanation about the mechanism and calculation of this model.

3.11. Multiphase pressure loss model

Multiphase pressure losses can be defined as a pressure loss due to existence and flow of multiple phase of fluids in a wellbore system. These multiple phase can be essentially more than two-phase but not three-phase such as solid–liquid, liquid–liquid, gas–liquid, or gas–liquid phases. In this particular case, we assume that gas–liquid phases are considered an influx when a well control event has occurred. Compared to single-phase, multiphase flow is much more complex where there is no linearity, the flow transition from laminar to turbulence, and the characteristics two phase instabilities such as motion and deformation of the interface, the effect of non-equilibrium and the interaction between phases [61]. The total pressure loss of a fluid is made up of the sum of the difference of potential energy (hydrostatic), kinetic energy (acceleration), and friction energy on the walls of the flowing channel. This energy balance, which is basic to all pressure loss calculation, can generally be written as:

$$V_3 = \Delta P_{static} + \Delta P_{friction} + \Delta P_{kinetics} \quad (14)$$

$$-\frac{dp}{dz} = g\rho_m + \frac{f_m v_m^2 \rho_m}{2d} + \rho_m v_m \frac{dv_m}{dz} \quad (15)$$

For most vertical and inclined wells, the hydrostatic head component directly depends on the mean volume density of the mixture, ρ_m (dominates). Therefore, two-phase flow modelling boils down to estimating the density of the fluid mixture or the volume fraction of gas [62]. While, the determination of frictional head losses also require an estimate of the mixture density and hence the gas volume fraction in the pipe [63]. The mixture density, ρ_m, is the volumetric-weighted average of the two phase, the density of liquid, ρ_L , and the density of gas, ρ_g.

$$\rho_m = \rho_g f_g + \rho_L (1 - f_g) \quad (16)$$

To determine the in-situ volume fraction of the gas phase or lighter phase in the liquid flow, f_g, a two-phase flow model of two-phase friction factor, f_m, is also requires due to the fact the volume fraction is often not equal to the ratio of the superficial gas velocity, v_g to the average velocity of the mixture, v_m.

$$f_g \neq \frac{v_{sg}}{v_m} \quad (17)$$

Applying the homogenous model to estimate the frictional pressure, the friction factor, f_m, in all flow regimes is determined from the Reynolds number of the mixture, Re_m, which uses a mass-average mixture viscosity, μ_m [62].

$$Re_m = \frac{D v_m \rho_m}{\mu_m} \quad (18)$$

$$\mu_m = \mu_g x + \mu_l (1 - x) \quad (19)$$

Chen's correlation (1979)[64] for the friction factor, f_m, in rough pipes is then applied. Chen (1979) proposed the following equation for the friction factor covering all the ranges of the Reynolds number and the relative roughness [65].

$$f_m = \frac{1}{\left[4\log\left(\frac{\varepsilon/d}{3.7065} - \frac{5.0452}{Re_m}\log A\right)\right]^2} \quad (20)$$

Where ε is the pipe roughness and A is the dimensionless parameter given by equation:

$$A = \frac{(\varepsilon/d)^{1.1098}}{2.8257} + \left(\frac{7.149}{Re_m}\right)^{0.8981} \quad (21)$$

Regarding the volume fraction of gas f_g, it depends on the flow conditions of the fluid, whether the flow is bubble, slug, churn or annular [62]. The flow patterns found in the vertical well are shown in Fig. 2.

For all flow regimes, the gas phase (or lighter) moves faster than liquid (or heavier), due to its buoyancy and its tendency to flow close to the channel centre, where the gas velocity is greater than the average mixture velocity. This allows to express in-situ gas velocity, vg, as the sum of bubble rise velocity, v_∞, and the dimensionless flow parameter, C_o, the time average mixture velocity, v_m. [62].

$$v_g = C_o v_m + v_\infty \quad (22)$$

where the average mixture velocity, v_m, for concurrent vertical upward flow is given by:

$$v_m = v_{sg} + v_{sl} \quad (23)$$

And when counter current, the liquid flows downwards while the gas flows upward, the average mixture velocity is given by:

$$v_m = v_{sg} - v_{sl} \quad (24)$$

Stated that the in-situ gas velocity is the ratio of the superficial velocity to the gas fraction by volume, it can simple relate the volume fraction to the phase velocities in these flow regimes. The plus sign in the v_∞ shows an increase and the negative sign indicates a decrease in the rate of bubble rise velocity. It is observed that the bubble rise velocity decreases with increasing pressure and decreasing temperature [70]. The increasing velocity of a spherical bubble increases with increasing bubble size, as the increase in the body force (buoyancy) dominates the increase in friction in this shape regime [71].

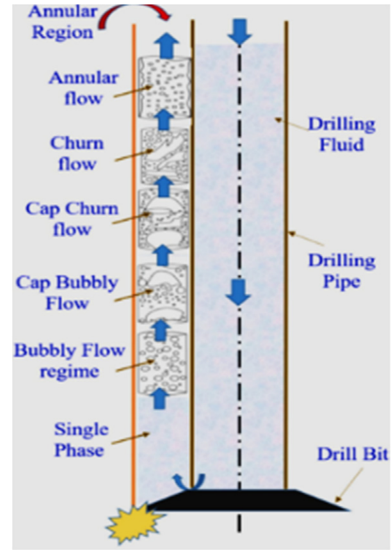


Fig. 2. Variation of flow patterns for upward vertical wellbore during Gas kick scenario [4,66–69].

$$f_g = \frac{v_g}{C_o v_m \pm v_\infty} \quad (25)$$

where the calculated volume fraction, f_g, is then can be substitute in average mixture density equation, [62];

$$\rho_m = \rho_g f_g + \rho_L (1 - f_g) \quad (26)$$

The value of the dimensionless flow parameter, C_o, and the bubble rise velocity, v_∞, depend on the flow pattern, the well deviation, the flow direction whether upward or downward, and phases which will directly affect the volume fraction, f_g. Table 3 show the values for each type of flow type and respective flow patterns.

3.12. Well input parameters

Information on the high pressure high temperature well is obtained from the well drilled by PETRONAS. Tables 4 and 5 shows the input parameters used in both single bubble gas modelling and dynamic multiphase simulation.

Table 6 shows the input parameters in order to carry out the simulation. These parameters are taken into account to calculate the dynamic multiphase kick tolerance.

Depending on the design of the well, to determine the kick tolerance, the kick is always defined as a swabbed kick instead of a kick when drilling where the main concern is after drilling the 8 ½″ hole section where the mud weight will always be 150 psi overbalance to the pore pressure and the kick is avoidable. Therefore, a swabbed kick event is a kick with a reservoir pressure at the target depth that occurs when tripping drill pipe out of hole without circulating. Based on above condition in Table 6, simulation for dynamic multiphase is performed and compared to the single bubble gas phase to determine the significant difference of maximum allowable kick volume in a well as an influx enter and circulate out without fracturing the shoe.

3.13. Kick tolerance for single bubble gas phase

This phase consists of calculating the kick tolerance for the single bubble gas phase model in order to calculate the kick volume

Table 3
Parameter for flow type and flow pattern [62].

Flow Pattern	Flow Parameter, Co			Rise Velocity v_∞
	Upward concurrent	Counter current	Downward	
Bubbly	1.2	2.0	1.2	∞b
Slug	1.2	1.2	1.12	∞
Churn	1.15	1.15	1.12	∞
Annular	1.0	1.0	1.0	0

Table 4
Basic HPHT well input parameters.

Well Properties	Total Vertical Depth	ft	15,549
	Last casing setting depth	ft	12,796
	Open hole size	in	8.5
	Drill pipe outer diameter	in	5.5
	Drill collar outer diameter	in	6.5
	Drill collar length	ft	328
	Open hole length	ft	2,753
Formation Properties	Pore Pressure	ppg	16.15
	Fracture Pressure	ppg	18.00
	Gas gradient	psi/ft	0.1
		ppg	1.9
	Temperature	F°/ft	0.02
		F°	340.0
Mud Properties	Mud type	–	WMB
	Mud weight	ppg	16.33
	Yield point	lb/100ft^2	22
	Plastic viscosity	cp	21

for a given parameter for a well. Basically the modelling contain the well info such as reservoir properties at TD, fracture pressure at shoe, depth for both TD and CSD, mud used properties, and bore hole geometry of open hole and drill string that needed to be input. Then, the kick volume of influx is calculated based on this information and the formulated equation from kick tolerance calculation. The procedures to construct the single bubble gas phase model are as follows: 1. Collection of well data information such as well type (HPHT), depth (target depth and last casing depth), formation, mud, hole geometry. 2. Finalized the condition and cases to be investigated as the final response in this modelling (i) Case 1: the response of maximum allowable kick volume when constant pore pressure and fracture pressure, while increasing the mud weight used (as shown in Fig. 3). (ii) Case 2: the response of maximum allowable kick volume when increasing of pore pressure and mud weight while constant fracture pressure (as shown in

Table 5
Parameters for dynamic multiphase simulation.

Item	Detail of assumption		
Well Properties	Well trajectory is vertical		
Reservoir Properties	Swabbed Kick, Dry Gas, Influx Rate = Constant 3 bbls/min, Permeability = 200mdc, Porosity = 15%		
Mud Properties	Mud Type	WBM	SBM
	Based Oil Density	6.2591 lbm/USgal	6.5569 lbm/USgal
	Water Density	8.3454 lbm/USgal	8.5956 lbm/USgal
	Solid Density	31.8628 lbm/USgal	35.0508 lbm/USgal
	Oil/Water Ratio	0/100	80/20
	o Mud weight must be 150 psi overbalance from pore pressure at TD o PV = 55 cp, YP = 21 lbf/100ft2, Fann Reading 3 rpm = 9 lbf/100ft2 o Reference Temperature = 120F o Rheology Model = Robertson-Stiff		
Circulation Method	○ Driller's Method (Constant bottomhole pressure) ○ Circulation rate = 100 Gal/min ○ Dynamic Safety Margin = 100 psi		
Initial Pre-Kick Condition	○ Initial Pump Rate = 0 Gal/min ○ Initial ROP = 0 ft/hr		
Sub Models	○ Two Phase Pressure Loss Model = Semi-Empirical ○ PVT Model = Compositional		
Surface Equipment Properties	Choke line	○ Length = 15 m ○ ID = 3.5″ ○ No of chokeline = 1 ○ Duration Closure = 0.08 min ○ Pressure after choke at surface = 14.7 psi	
	Pump	○ Liquid Pump Rate Change = 500 Gal/min^2 ○ Pump Output = 6.27 Gal/stroke ○ Delay Pump Shutdown = 0.05 min	
	BOP	o Duration Closure = 0.25 min o Delay until BOP Closure = 0.05 min	
Temperature Properties	○ Temperature Model = Holmes & Swift Model. ○ Mud Temperature ○ HPHT ○ Drillstring injection temperature = 147.2F ○ Chokeline outlet temperature = 165.2F ○ Heat Transfer Coefficient ○ HTC across drillpipe = 0.008 Btu/s*ft2*F ○ HTC across wellbore = 0.000 Btu/s*ft2*F		

Table 6
Comparison of kick volume for dynamic multiphase and single gas phase by increasing mud weight using water based mud at constant pore pressure and fracture pressure.

Pore Pressure (ppg)	Fracture Pressure(ppg)	Unc. (ppg)	Water Based Mud-Mud Weight (ppg)	Kick Volume, bbl	
				Single Gas Phase	Dynamic Multiphase
16.15	18.00	0.0	16.33	55.5	203.0
16.15	18.00	0.2	16.53	48.2	219.2
16.15	18.00	0.4	16.73	40.9	183.8
16.15	18.00	0.6	16.93	33.4	173.3
16.15	18.00	0.8	17.13	26.0	159.1
16.15	18.00	1.0	17.33	18.9	139.1

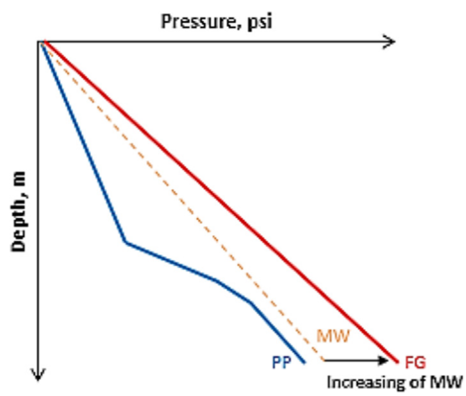


Fig. 3. Constant pore pressure and fracture pressure by varying mud weight for water based mud & synthetic based mud.

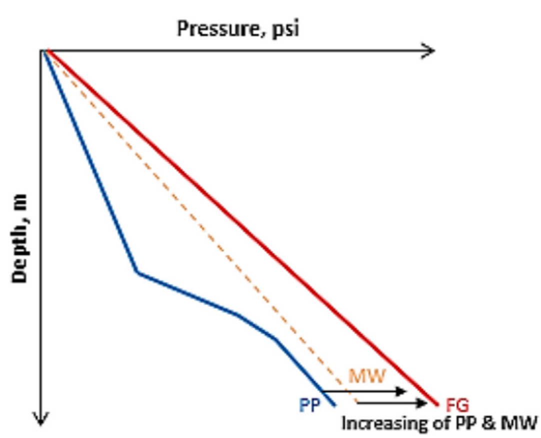


Fig. 4. Constant fracture pressure by varying pore pressure and mud weight for water based mud & synthetic based mud.

3.14. Kick tolerance for dynamic multiphase

This phase consists of determining the kick tolerance for dynamic multiphase by simulation with dynamic well control software that simulates a well control event when the kick is introduced, followed by the standard well control procedure of shutting down the pumps and closing the BOP, then allow the bottom hole pressure to be constant before circulating out the influx. Before running the simulation, it is required to input basic data such as well trajectory, wellbore geometry, drill string assembly, surface equipment used, fracture pressure, drilling fluid properties, reservoir properties, and temperature. Then, simulations are performed to obtained the kick sensitivity analysis in variable parameter of mud weight used, reservoir pressure, pit alarm level, and kill circulation rate to check the maximum allowable kick volume during shutting in well and circulating influx out to surface before the casing shoe reach its fracture pressure. Simulating of the flow is carried with real time data on pit gain, pressure at casing shoe, pump and choke pressure at surface, gas flow rate out, and also free gas and dissolved gas volume fraction in wellbore during influx entry the wellbore and circulate out to surface is the resulted response. The step by step procedures to simulate dynamic multiphase kick tolerance are presented as follows: 1. Inputs were defined into the numerical model in order to run the simulation. Following are the required data information for simulation (i) Well trajectory, (ii) Wellbore geometry, (iii) Drillstring assembly, (iv) Surface equipment, (v) Fracture pressure, (vi) Mud properties, (vii) Reservoir properties, (viii) Temperature. 2. A semi-empirical model is selected for pressure losses calculations. 3. Before proceed to run configuration, the desired result and cases to be seen as the final result in this simulation is mapped out separately which has been similar to the single bubble gas phase modelling for comparison purpose. (i) Case 1: the result of maximum allowable kick volume when constant pore pressure and fracture pressure, while increasing the mud weight used (as seen in Fig. 3). (ii) Case 2: the result of maximum allowable kick volume when increasing of pore pressure and mud weight while constant fracture pressure (as seen in Fig. 4). 4. Run configuration is then performed to simulate kick sensitivity in variable parameter of mud weight, reservoir pressure, pit alarm level and pit gain at shut-in, and kill circulation rate. In this research, a variation value of pit alarm level has been input while other parameter will remain constant respectively to each cases in order to check the maximum allowable kick volume during shutting in well and circulating influx out to surface before the casing shoe reach its fracture pressure. 5. Simulations for sensitivity analysis is then performed to check kick tolerance for dynamic multiphase. During simulation, real time result data on pit gain, pressure at casing shoe, pump and choke pressure at surface, gas flow rate out and also free gas and dissolved gas volume fraction in wellbore is obtained. 6. As for the result on maximum allowable influx volume, it is generally referred to the maximum pit gain at surface during shut in and the shut-in influx volume is circulated out to surface without fracturing the casing shoe. Therefore, the limiting factor is the fracture pressure at shoe. 7.

Fig. 4). 3. Apply modifying kick tolerance calculation by considering three conditions of influx location to determine the most conservative response. (i) Calculated kick volume at shoe is transferred directly to the bottom-hole by applying Boyle's Law. (ii) When calculated height of influx is longer than the height of BHA, height of influx at shoe is transferred to bottom hole and influx volume is calculated based on the annular capacity for both drill-pipe and BHA. (iii) When calculated height of influx is shorter than the height of BHA, height of influx at shoe is transferred to top of BHA and influx volume is determined based on the annular capacity of BHA. Calculated influx volume then is been transferred to bottom hole by applying Boyle's Law. 4. Based on the well data information, equation stated in theory, both cases and three conditions above, kick volume is calculated. 5. Calculated influx volume for all three conditions are compared to each other, and the smallest value (more conservative value) is to be selected as the final response.

All gathered result is then compiled for comparison purpose with the single bubble gas phase kick tolerance. 8. Sensitivity analysis is performed on dynamic multiphase to check the significant impact on the kick volume.

4. Results and discussion

In this section, a comparison for both the single bubble gas phase and the dynamic multiphase kick tolerance is presented. The impact of parameter includes the properties of the reservoir, the fracture pressure, the properties of mud and type, the initial pre-kick condition and also the final response of influx volume, the pit-gain at shut-in, the casing pressure at shut-in, the choke pressure at shut-in, the choke pressure when influx at surface and also the flow rate influx at surface. The response of kick volume for single bubble gas phase and the result of pit-gain at shut-in for dynamic multiphase are compared. Similarly the response of kick volume is presented when different mud type is used which is synthetic base mud. Both result for water based mud and synthetic base mud on pit-gain at shut in are then compared. By simulation of a real time event of a kick as the well taken a kick and the well is shut-in, then the influx is circulated out to surface by applying the killing method. Through the numerical model, a real time result during the event of well control able to be obtained similarly like on a rig such as pit gain, choke pressure, pump pressure, gas flow rate out and casing shoe pressure.

4.1. Comparison between single bubble gas model with dynamic multiphase model

Fig. 5 (a-b) and Tables 6 and 7 show the comparison of the maximum allowable kick volume between the single bubble gas phase and the dynamic multiphase.

4.1.1. Constant pore pressure & fracture pressure, increase of mud weight using WBM

Maximum allowable kick volume between the single bubble gas phase and the dynamic multiphase for case 1 (see Fig. 5 (a) and Table 6), where the pore pressure and the fracture pressure are kept constant while the mud weight of a water based mud (WBM) is increased constantly with some uncertainty of 0.2, 0.4, 0.6, 0.8, 1.0 ppg compared to the base case. It can be clearly seen from Fig. 5 (a), for both the single bubble gas phase and the dynamic multiphase, the maximum allowable kick volume is decreasing as the mud weight used is increased with some uncertainty of 0.2, 0.4, 0.6, 0.8, 1.0 ppg. This is because when mud weight is increased, it increases the hydrostatic pressure exerted by the mud column at casing shoe and reduce the pressure difference gap between fracture pressure and hydrostatic pressure, which directly reduce the maximum allowable anticipated surface pressure (MAASP) of a well. Where lower MAASP indicates less tolerance to fracture the casing shoe and relatively decreases the maximum allowable kick volume when a well take a kick and the top of influx reaches and fracture the casing shoe.

As the influx enter the wellbore and BOP is shut-in, a kill procedure was performed to circulate out the influx to surface while maintaining bottom hole pressure, dynamic multiphase able to have more kick volume compare to single bubble gas phase before it fracture the weakest point which is the casing shoe. This can be explained when in single bubble gas phase, the pressure of top of gas for that particular gas volume as it reach to casing shoe is higher than the dynamic multiphase because it consider the gas pressure is exerted by 100% of gas column fraction. However, in dynamic multiphase, due to gas dispersion and solubility which cause a multiple phase of fluid inside the mud, the gas fraction is lesser than 100% (approximately 20% ~ 30%) and this had caused a pressure drop which lowered down the top of gas pressure as it reach the casing shoe and enter the casing without fracturing the casing shoe. Resulting the wellbore be able to accept more influx at the open hole section without fracturing the casing shoe since the gas pressure gradient below shoe is held constant.

4.1.2. Constant fracture pressure, increase of pore pressure and mud weight using WBM

Comparison of the maximum allowable kick volume between the single bubble gas phase and the dynamic multiphase for case 2, where the fracture pressure is kept constant while the pore pressure and the mud weight of a water based mud (WBM) is increased constantly with some uncertainty of 0.2, 0.4, 0.6, 0.8, 1.0 ppg over the base case is shown in Fig. 5 (b) and Table 7.

As shown in Fig. 5 (b), comparing between single bubble gas phase and dynamic multiphase, when the influx enter the wellbore and the BOP was shut-in, then killing procedure was performed to circulate out the influx to surface while maintaining bottom hole pressure, the trend is similar to case 1, However, for dynamic multiphase, as the pore pressure and the mud weight was increased more than 16.75 ppg and 16.93 ppg respectively, the maximum allowable kick volume had decreased drastically less than 50 bbl and much more nearer to the single bubble gas phase. This can be explained firstly due to the increasing of pore pressure at bot-

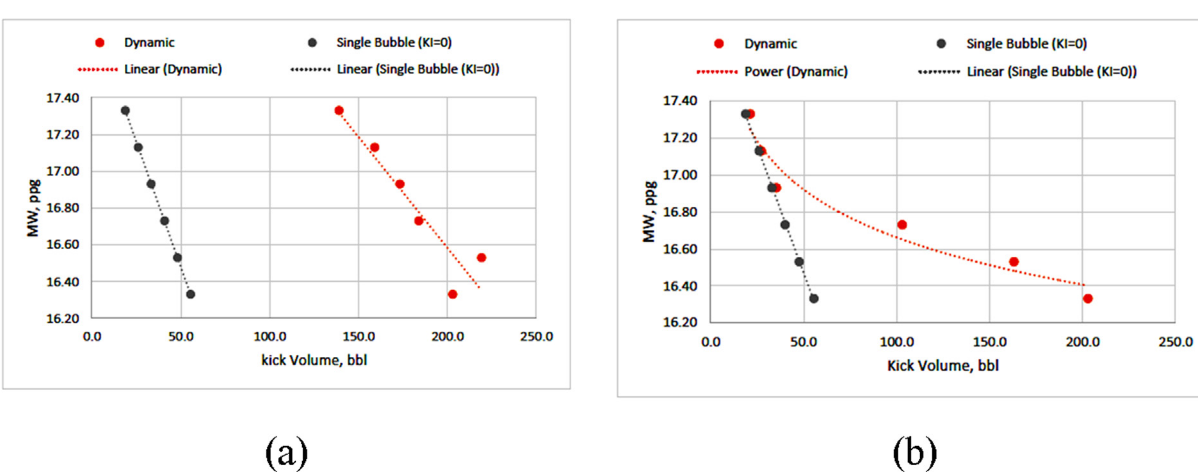


Fig. 5. Kick volume for both dynamic multiphase and single bubble (a) at constant pore pressure & fracture pressure by varying mud weight of water based mud, (b) at constant fracture pressure and varying pore pressure as well as mud weight using water based mud.

Table 7
Comparison of kick volume for dynamic multiphase and single gas phase by increasing pore pressure, mud weight using water based mud at constant fracture pressure.

Pore Pressure (ppg)	Fracture Pressure (ppg)	Unc. (ppg)	Water Based Mud-Mud Weight (ppg)	Kick Volume, bbl	
				Single Gas Phase	Dynamic Multiphase
16.15	18.00	0.0	16.33	55.5	203.0
16.35	18.00	0.2	16.53	48.2	163.1
16.55	18.00	0.4	16.73	40.9	103.1
16.75	18.00	0.6	16.93	32.9	35.4
16.95	18.00	0.8	17.13	26.0	27.2
17.15	18.00	1.0	17.33	18.9	21.3

tom hole which induce more influx to enter the wellbore in higher influx mass rate. It is noticed that where the influx mass rate increase as the reservoir pressure (pore pressure) increase. The second reason is due to the increasing of mud weight used during pre-kick condition. As the mud weight increase, it reduces the pressure gap between fracture pressure of the formation and hydrostatic pressure exerted by the mud column below the casing shoe which directly reduces the maximum allowable anticipated surface pressure (MAASP). Where lowered the MAASP reflect to a lesser height of influx and kick volume. Similarly to case 1, based on observation from Fig. 5 (b), for both single bubble gas phase and dynamic multiphase, the maximum allowable kick volume is decreasing as the mud weight used is increased with some uncertainty of 0.2, 0.4, 0.6, 0.8, 1.0 ppg. This is because when mud weight is increased, it increases the hydrostatic pressure exerted by the mud column at casing shoe and reduce the pressure difference gap between fracture pressure and hydrostatic pressure, which directly reduce the maximum allowable anticipated surface pressure (MAASP) of a well. Where lower MAASP indicates less tolerance to fracture the casing shoe and relatively decreases the maximum allowable kick volume when a well take a kick and the top of influx reaches and fracture the casing shoe.

4.2. Sensitivity analysis

A sensitivity analysis is performed on dynamic multiphase to check the significant impact on the kick volume. Below is the list of the sensitivity analysis carried out in this study: (i) Different mud types used which are Synthetic Based Mud (SBM) and Water Based Mud (WBM). (ii) Different based oil composition of SBM where to check the compressibility effect of the mud. Different carbon compound number with certain percentage of mole fraction is inputted. (iii) Different circulation kill rate is selected ranging from 100 gpm to 200 gpm is selected. Sensitivity analysis is also performed on difference mud type used, different based oil composition of SBM, and different circulation kill rate for dynamic multiphase kick tolerance.

4.2.1. Comparison of kick volume between different mud type (WBM vs SBM):

This section presents sensitivity analysis to investigate the impact of different mud type on the maximum allowable kick volume for dynamic multiphase as shown in Fig. 6 (a-b). The sensitivity analysis has been performed for both cases where two type of mud has been used during simulation which is water based mud for the basic input and synthetic based mud as the variable parameter.

Tables 8 and 9 show the sensitivity analysis of the kick volume in both cases, when different types of mud has been used such as water based mud (WBM) and synthetic based mud (SBM). In comparing the amount of maximum allowable kick volume between WBM and SBM, WBM allows more kick volume compare to SBM as the well is shut-in and the influx is circulate out before it fracture the weakest point which is the casing shoe. This can be explained by considering the Equivalent Circulating Density (ECD) and Gas Solubility and Compressibility for both mud used during the event of taking and circulating influx out to surface.

First, regarding the explanation on the ECD, two conditions of pre-kick and killing situation have been considered in determining the ECD, where ESD during the pump is already switch off as the kick taken to simulate the swabbed kick and the ECD of killing rate during circulate influx out to surface. Tables 10 and 11, for WBM show that when the kick start to take in, the pump was already switched off, found out that the ESD (ECD when pump off) of WBM is reduce 0.3 ppg (approximately) from the initial mud weight used compare to the ESD of SBM which only reduce 0.01 ppg (approximately) which mean ESD of WBM is lower than ESD of SBM after the reduction. The reduction of mud weight at bottom hole when the pump is switch off is due to the temperature effect behave differently in both WBM and SBM. However, in SBM the variant reduction is not significantly because of SBM having a

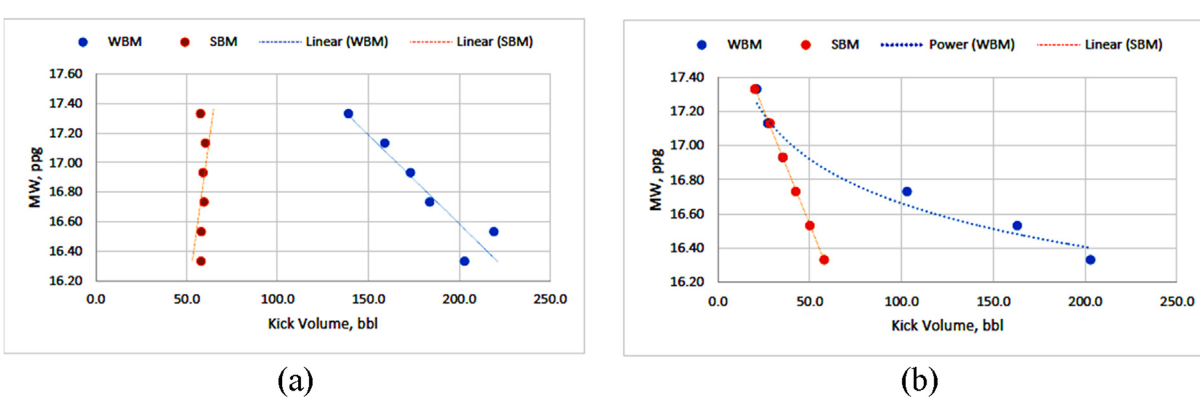


Fig. 6. Kick volume of dynamic multiphase between water based mud & synthetic based mud (a) at constant pore pressure of HPHT Well (b) at variable pore pressure of HPHT Well.

Table 8
Comparison kick volume of dynamic multiphase between water based mud (WBM) and synthetic based mud (SBM) at constant pore pressure of HPHT Well.

Pore Pressure (ppg)	Fracture Pressure (ppg)	Unc. (ppg)	Water Based Mud-Mud Weight (ppg)	Kick Volume, bbl	
				Synthetic Based Mud	Water Based Mud
16.15	18.00	0.0	16.33	58.0	203.0
16.15	18.00	0.2	16.53	58.1	219.2
16.15	18.00	0.4	16.73	59.6	183.8
16.15	18.00	0.6	16.93	59.1	173.3
16.15	18.00	0.8	17.13	60.4	159.1
16.15	18.00	1.0	17.33	57.7	139.1

Table 9
Comparison kick volume of dynamic multiphase between water based mud (WBM) and synthetic based mud (SBM) at variable pore pressure of HPHT Well.

Pore Pressure (ppg)	Fracture Pressure (ppg)	Unc. (ppg)	Water Based Mud-Mud Weight (ppg)	Kick Volume, bbl	
				Synthetic Based Mud	Water Based Mud
16.15	18.00	0.0	16.33	58.0	203.0
16.35	18.00	0.2	16.53	50.1	163.1
16.55	18.00	0.4	16.73	42.5	103.1
16.75	18.00	0.6	16.93	35.4	35.4
16.95	18.00	0.8	17.13	28.3	27.2
17.15	18.00	1.0	17.33	20.1	21.3

Table 10
Equivalent static density and equivalent circulating density of water based mud weight.

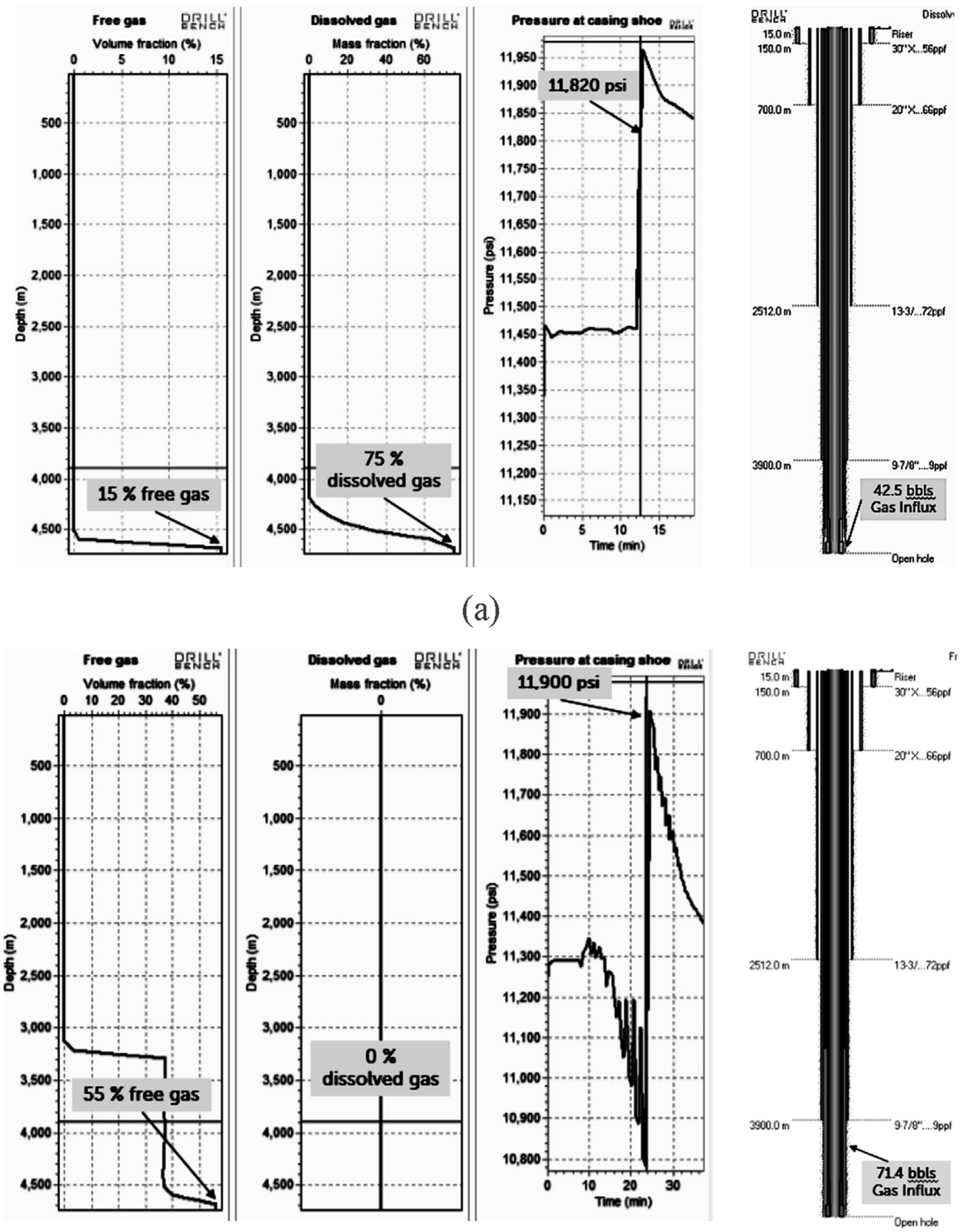
Mud Weight (ppg)	Equivalent Static Density (Pump Off)	Equivalent Circulating Density (Kill Rate)	Equivalent Static Density Gap (MW-ESD)	Equivalent Circulating Density Gap (MW-ECD)
16.33	16.04	16.47	−0.29	+0.14
16.53	16.20	17.03	−0.29	+0.50
16.73	16.44	17.23	−0.29	+0.50
16.93	16.65	17.44	−0.28	+0.51
17.13	16.85	17.64	−0.28	+0.51
17.33	17.05	17.84	−0.28	+0.51

Table 11
Equivalent static density and equivalent circulating density of synthetic based mud weight.

Mud Weight (ppg)	Equivalent Static Density (Pump Off)	Equivalent Circulating Density (Kill Rate)	Equivalent Static Density Gap (MW-ESD)	Equivalent Circulating Density Gap (MW-ECD)
16.33	16.31	16.72	−0.02	+0.39
16.53	16.52	16.93	−0.01	+0.40
16.73	16.72	17.13	−0.01	+0.40
16.93	16.92	17.33	−0.01	+0.40
17.13	17.13	17.53	−0.00	+0.40
17.33	17.33	17.74	−0.00	+0.41

higher compressibility factor which lead to a high ESD. When a higher reduction of mud weight is seen (lower ESD), the more tolerance between fracture pressure and hydrostatic pressure at shoe, and the more influx volume of a well can handle during the kick take place. Since dynamic multiphase also simulate the event when circulating influx out, even WBM has more 0.1 ppg ECD than SBM, however the dynamic pressure during mud pump is switch on and circulating with kill rate still manageable within the fracture pressure range at shoe by controlling the opening choke to make sure constant bottom hole pressure.

Second, for the solubility and compressibility of the gas in the WBM, the influx gas begins expanding as it start circulating uphole and it can generally be said that the size doubled up when the pressure is reduced by half. This means that as the gas influx expanded when it circulated out to surface, it pushed out the mud out of the well and replaced the mud column in wellbore, causing an incremental of pit gain and a reduction of the hydrostatic pressure as well as the bottom hole pressure. While in SBM or OBM, since the hydrocarbon component exists inside the mud, it has the compressibility characteristic. Therefore, the gas influx will dilute inside the mud and stays in solution and act in the same way as liquid until it reach gas bubble point, then suddenly breaks out solution and expands rapidly with pressure hiked up [49]. Fig. 7 (a-b) for dynamic multiphase flow analysis (Case 2-MW 16.73 ppg, PP 16.55ppg, FG 18.0 ppg, both WBM and SBM), during shut-in, in SBM, 75% of gas influx dissolved in mud (10–20% at top of gas) and only 15% free gas at bottom hole with 11,820 psi of casing shoe pressure. However in WBM, 60% of gas influx is in free gas form and zero gas influx dissolved in mud at bottom hole with 11,900 psi of casing shoe pressure. This showed that with an approximately same casing shoe pressure during shut-in, in SBM has more gas dissolved in mud but less free gas at bottom hole compare to WBM has more free gas at bottom hole but zero gas dissolved, where pit gain at surface indicates the mud volume that is displaced by a volume of influx gain at down-hole in a free gas form. By this, we can conclude that, in SBM has less pit



(b)

Fig. 7. Dynamic multiphase flow response on gas solubility and free gas (a) for synthetic based mud (b) for water based mud.

gain (influx volume) compare to WBM due to less free gas volume that displace the mud at bottom hole.

4.2.2. Compressibility effect of SBM

Regarding the compressibility effect, an additional simulation was run separately to test and justify the compressibility effect of the mud on the maximum kick volume. The simulation is only focused on SBM mud type since it has the compressibility characteristic. In order to determine the compressibility effect for SBM, variable parameter on mud PVT properties has been change, where different types of base oil composition having a different percentage of carbon compound number has been selected at the mud basic data input. As normal hydrocarbon chain length increases (in this case referring to carbon compound number increases), the compressibility of the hydrocarbon should decrease slightly [72]. The compressibility effect of higher molecular weight in polyethylene (higher carbon compound in polyaromatic), found out that the compressibility effect is negligible as the chain length increases in partially amorphous and crystalline polymer [72]. It can be concluded that as the carbon compound number of base oil composition increase, the compressibility effect of the base oil composition should decrease. Based on the list of base oil composition above, dynamic multiphase simulation for case 2 (PP = 16.15 ppg, MW = 16.33 ppg, FG = 18.0 ppg) is performed where the base oil composition of low toxicity of a SBM is selected as default input. Then, a different base oil composition of diesel and paraffin are selected from the simulation default list where these base oil has a vary percentage of carbon compound number. In order to further investigate on the base oil composition effect, several custom input on the carbon compound number has been made, by inputting 100% for each carbon compound number from range C11 until C20 + to represent the base oil composition of a SBM. Furthermore,

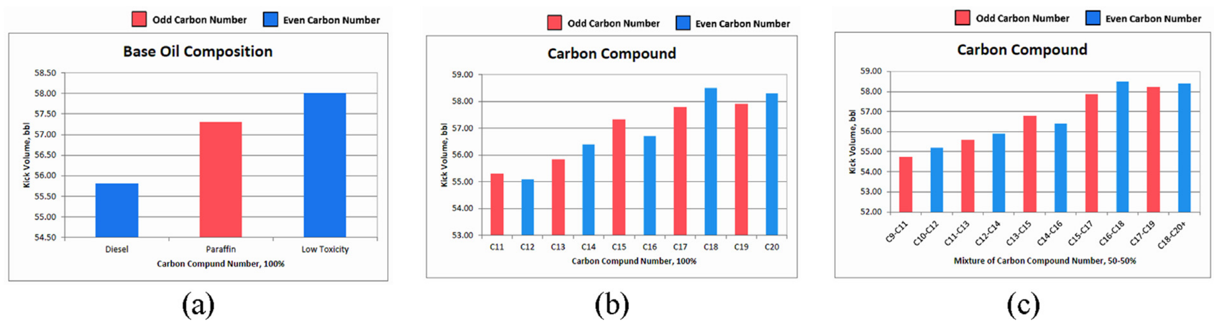


Fig. 8. Maximum kick volume based on different base oil composition and different carbon compound number (a) based on different base oil composition (b) each carbon compound consists of 100% mole fraction (c) carbon compound consists of the mixture carbon compound by pairing 50–50 percentage mole fraction.

a mixture of this carbon compound is also been made, by inputting 50–50 percentage for each carbon compound by pairing it into even-even and odd-odd number of carbon compound.

Fig. 8 (a) shows how the compressibility effect of the different composition of base oil, paraffin and low toxicity impact the maximum allowable kick volume. As the compressibility effect decrease, the maximum allowable kick volume increase, while as the compressibility effect increase, the maximum allowable kick volume decrease. Combining the idea from the above literature review in this section, as the carbon compound number increases, the compressibility effect of the hydrocarbon chain should decreases. It has been found that base oil composition of low toxicity has higher kick volume compare to paraffin and diesel where low toxicity has higher percentage of higher carbon compound number (C16 = 58.3%, C18 = 33.7%) compare to paraffin (C15 = 100%) and diesel (C12 = 42.8%, C16 = 55.4%). This indicates that due to higher number of carbon compound, low toxicity has lesser compressibility effect and directly increases the maximum allowable kick volume. However as for diesel, it has a lower number of carbon compounds, which indicates higher compressibility effect and directly decreases the maximum allowable kick volume.

Fig. 8 (b) shows the relations result between carbon compound number of a base oil composition and maximum allowable kick volume where each carbon compound consists of 100% mole fraction. Similarly, Fig. 8 (c) also shows the same relation between carbon compound number and kick volume but the carbon compound consists of the mixture carbon compound by pairing 50–50 percentage mole fraction of even-even and odd-odd carbon compound number. From Fig. 8 (b-c), it can be observed that as the odd carbon compound number increases from C11 to C19, the maximum allowable kick volume also increases. Similarly to the even carbon compound number, as the number increases from C12 to C20+, the maximum allowable kick volume also increases. This can be explained because as the carbon compound number increases, the chain length of the carbon compound also increases. When the chain length of carbon increases, it will have a higher molecular weight, which in turn lessens the spaces between molecular that they can be compressed or travel. As the result, it slightly decreases the compressibility effect of the chain which made the compound to be more incompressible equally to the Water Based Mud (WBM) characteristic. Thus, this result comparatively show the effect of the compressibility effect to the maximum allowable kick volume and to confirms the literature review that has been conducted previously in this section. As discuss, it can be concluded that the carbon compound number impact the compressibility effect of the base oil composition and directly affect the maximum allowable kick volume, where higher carbon compound number will have a lesser compressibility effect and directly increases the maximum allowable kick volume in a well. This statement consequently support the result where WBM has a bigger kick volume compare to SBM due to the lower compressibility effect.

4.2.3. Effect of different circulation kill rate

This section presents the result where a sensitivity analysis was conducted to see how the change of different circulation kill rate will effect on the maximum allowable kick volume for dynamic multiphase simulation. The sensitivity analysis has been performed for case 2 (PP = 16.15ppg and MW = 16.33ppg) only by using SBM where the variation of circulation kill rate is 100, 150 and 200 gpm. The base circulation kill rate for this simulation is 100 gpm. Fig. 9 shows the sensitivity analysis on different circulation rate (red = 100gpm, green = 150gpm, blue = 200gpm) for case 2 (PP = 16.15ppg , MW = 16.33ppg) where the figure consist the graphical result of pit gain, pump pressure, gas flow rate out, choke pressure, free gas and dissolved gas fraction and pressure at casing shoe versus time. Based on the observation, the maximum kick volume of an influx (referring to pit gain) at shut in does not change (exactly at 58 bbl) as the circulation kill rate increases from 100 gpm to 200 gpm. It shows that for all circulation kill rate, initially as the influx enter the well and shut-in at 58bbl, the casing shoe pressure (11,819 psi) still below the fracture pressure (11,979 psi). Then, when the pump is switch on to circulate out the influx, the casing shoe pressure hiked up (11,878 psi) but still does not exceed the fracture pressure. Therefore, the well able to contain and circulate out the influx without fracturing the shoe as the circulation kill's rate increase. However, it can be seen that the circulation kill rate has consequently affect the pump pressure and the gas flow rate out. When the pump is switch on, the pump pressure increases as the circulation rate increases, where at 100 gpm the pump pressure is 218.22 psi, at 150 gpm it increases 26.9% (276.97 psi) and at 200 gpm it increases 61.6% (352.65 psi). This is due to incremental of ECD at bottom hole can be seen at higher circulation kill rate.

Furthermore, as the influx is circulated out to surface, it can be seen that as the circulation kill rate increases, it significantly increases the gas flow rate out at surface. Where at 100 gpm the gas flow rate out is 2102 scf/min, at 150 gpm it increases 52.4% (3204 scf/min) and at 200 gpm it increases 108% (4372 scf/min). This can be explained that the gas influx expands and travel to the surface at higher velocity as the circulation kill rate increases. When the influx reach at surface, at 100 gpm the top of gas velocity is 3.829 ft/s, at150 gpm the velocity increases (5.420 ft/s) and at 200 gpm the velocity increases (6.557 ft/s) as shown in Fig. 10. A two-phase gas/liquid flow model taking into account a sudden change in density shows that the deeper the well, the smaller the gas flow, the smaller the distance between the separator and the bit, the difference density between light and heavy drilling fluid is small, and the larger the displacement. All these factors lead to the decrease in the variation of the annular outflow [73].

Further simulation has been carried out at different PP and MW to justify the effect of different circulation kill rate if the PP and MW are increased for the sensitivity analysis as shown in Fig. 11.

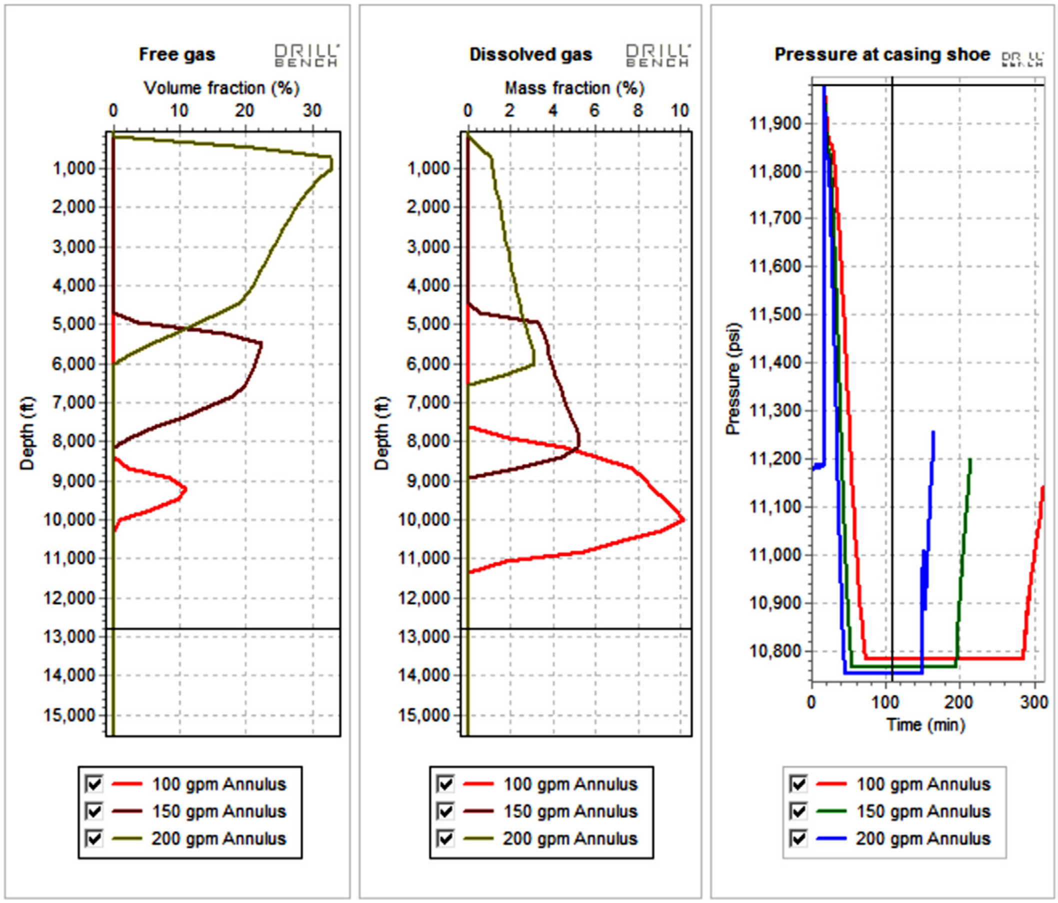


Fig. 9. Effect of different circulation rate for pore pressure = 16.15ppg & mud weight = 16.33ppg.

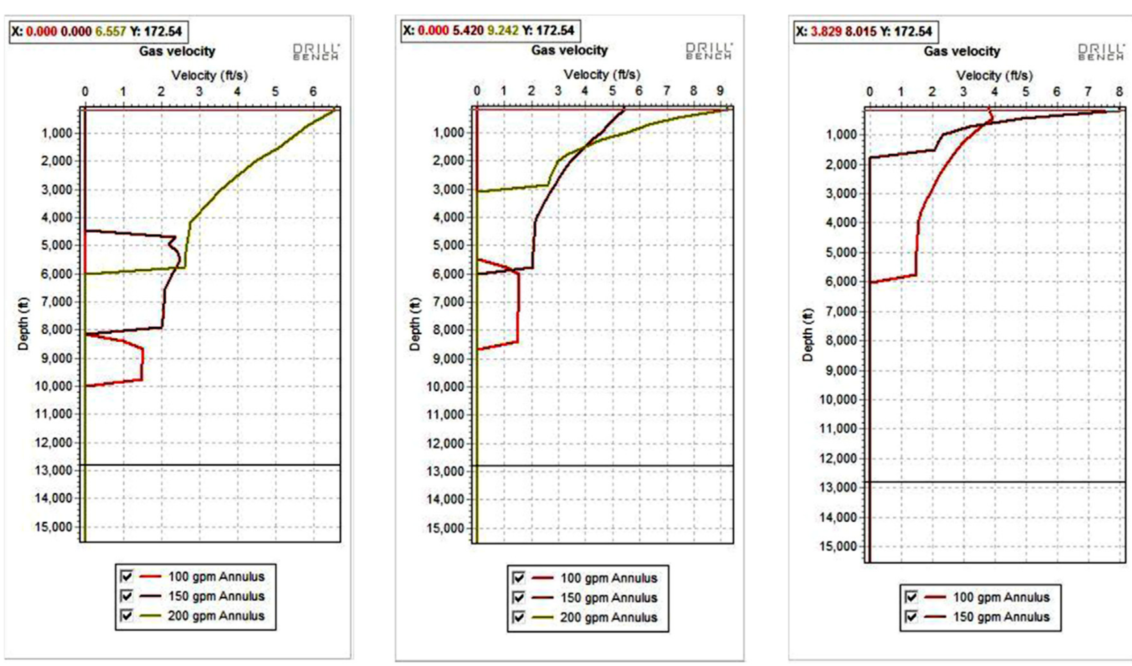


Fig. 10. Gas influx velocity at surface for different circulation rate.

It can be seen from Fig. 11 (a-b) that when the PP and MW are increased, the maximum allowable kick volume (pit gain) at shut-in also does not change when the circulation kill rate increases from 100 gpm to 200 gpm. It has the similar trend result as previous case and can be explained that this is due to the casing shoe pressure still below the fracture pressure as the pump is switch on and started to circulate out influx from the well. As for the effect on pump pressure and gas flow rate out, it also has the same trend

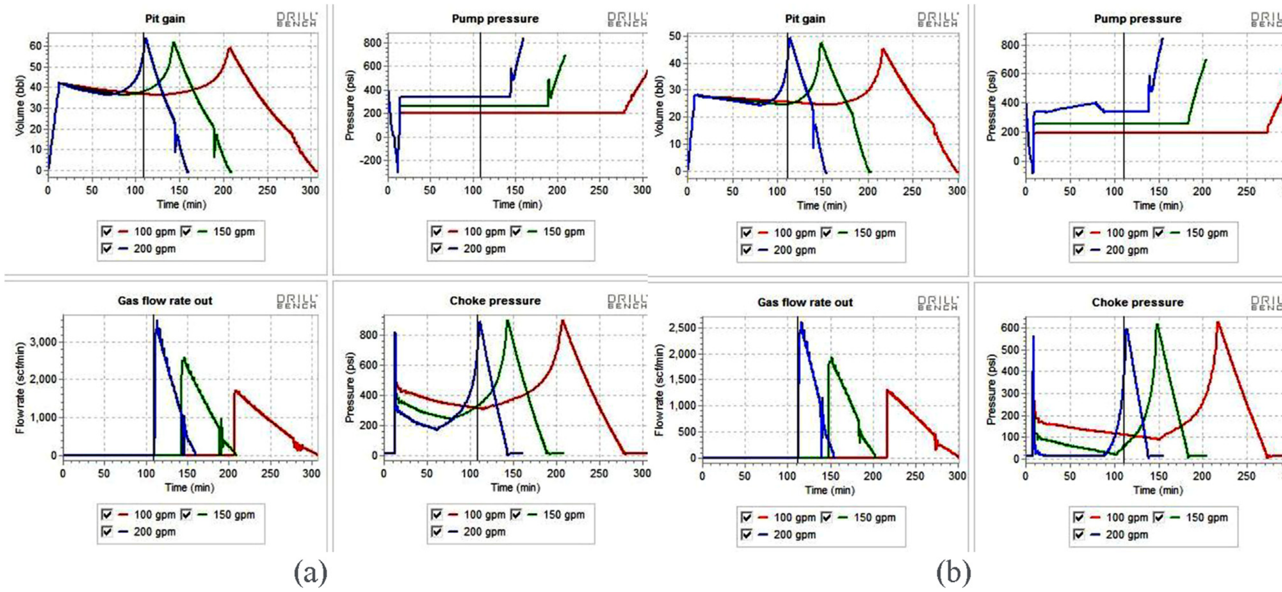


Fig. 11. Effect of different circulation rate (a) pore pressure = 16.55ppg & mud weight = 16.73ppg (b) pore pressure = 16.75ppg & mud weight = 16.93ppg.

result whereas the circulation kill rate is increases, the pump pressure and the gas flow rate out also increases. The explanation for this result is similar as previous case, where it is due to the increasing of ECD as the pump is switch on and the increases of the influx velocity as it travel to the surface. As there is no accepted standard method in calculating the tolerance of an influx for the drilling industry where neither unconformity nor consistency in comparing result between operators. Based on the accuracy of the presented procedure, the prediction of kick tolerance from dynamic multiphase modelling can be used as a guideline to identify the behaviour of an influx when a kick event occurs.

5. Conclusion

Dynamic multiphase modelling is able to support more kick volume compared to single bubble gas phase modelling where it considers multiple fluid phase in an influx and applies the gas characteristic to have multiphase pressure loss. Dynamic multiphase provide greater kick tolerance when fracturing the weakest point at casing shoe, where the single bubble gas phase is more conservative when it allows influx. The Increased mud weight reduces the maximum allowable kick volume of an influx due to the reduction in MAASP between fracture pressure and hydrostatic pressure at casing shoe. Larger kick volume can be achieved when using water based mud (WBM) compare to synthetic based mud (SBM). Kick tolerance vary with the mud type used due to its mud rheology (PV and YP) which impact the mud ESD to drop more in WBM when pump is off. The reduction of mud weight (MW) in WBM and SBM is due to the different behaviour of the effect of temperature. However, having a higher compressibility factor in the SBM leads to a higher ESD which results in less kick volume. Decrease on the compressibility effect of the based oil composition in the SBM causing the increase in the maximum allowable kick volume and this is due to the increase in the number of carbon compound in the base oil composition. Where higher carbon compound having a long chain molecular structure which leads to a lower compressibility effect. The increase of circulation kill rate during circulating influx from bottom-hole out to surface does not affects the initial amount of kick volume as the influx enters the well and casing shoe pressure during shut-in. However, increasing the circulation kill rate has an impact on the pump pressure and increase gas flow rate. In addition, it also shortens the killing period.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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