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Simulation Investigation on Multiphase Kick Behavior and Kick Tolerance for Highly Deviated Fractured Basement Reservoirs

Osama Sharafaddin[1,2], Madya Issham Ismail[1], Mohamed Halafawi[2], Muhammad Subhi Sirajuddin[1], Gehad Mohammed Ahmed Naji[3]

[1] *Universiti Teknologi Malaysia (UTM), Malaysia*
[2] *Petroleum-Gas University of Ploiesti (UPG), Romania*
[3] *Universiti Teknologi PETRONAS (UTP), Malaysia*

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Abstract

There are various difficulties involved in drilling operations in the oil and gas industry. Well controlling is considered the most vital one. Therefore, this work investigates and analyses these pressure changes that act on these parameters during well control using Engineer's method. Since fractured basement is an important oil and gas contributor to the petroleum industry, a case study was conducted on a basement reservoir using Drillbench multiphase flow simulator for various kick size and various kick intensity 10, 50, and 80 bbl and 0.1, 1.0, and 1.5 ppg respectively. The sensitivity analysis proved that kick size and kick intensity have significant effect while circulating the kick. The bigger the size of kick the higher pressure profile was noticed. Similarly, an increase in kick intensity would result in increasing choke pressure, casing shoe pressure and pump pressure. Basement reservoirs have bigger kick size due to the high pressurized and fractured network that lead to complicate controlling the well. The obtained results greatly show the importance of defining kick tolerance and assist drilling rig operators to anticipate how dangerous is to underestimate gas kicks and appropriately manage to circulate the gas kick out of the wellbore safely.

Keywords: *Well control; Basement reservoirs; Kick intensity; Kick size; Kick tolerance.*

1. Introduction

Well control is an expression for all measures that can be applied to prevent uncontrolled release of wellbore effluent to the external environment or uncontrolled underground flow. A blowout is defined as uncontrolled of formation fluid that passes all well barriers and flow to the surface. A kick is defined as a sudden flow of formation fluids into a wellbore. Several types of fluid can enter a wellbore as a kick such as gas, hydrocarbons, formation water, or combinations of all these. Among these fluids, a gas kick is considered the most difficult to be handled due to its high compressibility and low density [1]. Kick may occur when the formation pressure is more than the wellbore pressure causing influx of gas from the formation into the wellbore. The main reason for gas kicks is insufficient mud weight that results in formation pressure exceeding the wellbore pressure. On the other hand, too much over pressuring the wellbore using heavy mud-weight is not a viable solution as it can cause fractures into the formation, which would lead to loss of circulation and formation damage [2].

Various methods for mud circulation and gas influx were applied into mathematical models. The final form of the model is depending on casing shut-in pressure, Drill pipe shut-in pressure, and the pit gain to find out the gas volume in the wellbore [3]. The annular pressure was analyzed during Driller's method and Engineer's method. He highlighted two cases when the gas influx flows as a continuous slug and when it is mixed with mud that determine the effect of formation permeability, kick volume, and wellbore geometry on annular pressure profiles at any depth of interest [1]. System of multiphase is remarkably vital in well control particularly in undesirable circumstances such as kicks. Flow behavior and pattern is different from one phase system where normally only gas kick is considered when design phase of the drilling campaign. Since the multiphase kick might represent different outcome compared to one phase system, an accurate calculation of multiphase kick is desired [4]. It has been studied different killing methods in different situations during drilling and workover operations and the factors that affecting killing procedures like kill rate, influx type, formation permeability, and ballooning effect. The study used DRLLSIM 5000 simulator for analyzes and investigation the results [5].

There are many problems that may occur during drilling, workover, snubbing, and coil tubing. To this extent, occurrence off a kick is considered a serious problem because making a mistake in well control may lead to a catastrophe. Particularly when gas kicks are not properly controlled which eventually can escalate into blowout. Thus, a quick, appropriate, and an effective response to well control is vital. Rig crew are required to fully understand and recognize the disastrous effect of kick size and determining the kick tolerance is the key that will be used either to kill the well by conventional methods or need to go with unconventional complicated methods. As basement reservoirs are mainly composed of fractures that lead to larger kick size, as a result would need more attention and accurate calculations. Furthermore, it was very difficult to identify kicks in the early days, but nowadays it is possible for the kicks to be detected thanks to the improved technology such as highly sensitive sensors, which are used to detect mud volume levels, flow rate of circulating fluids, measurement while drilling and also the flow rate of producing fluids [6].

Therefore, the main objective of this research work is to investigate the effects of circulating a kick on different parameters such as pit gain, casing shoe pressure, choke pressure, and drill pipe pressure while killing the well, and also develop an understanding of the behavior of gas kicks from the time the kick influx flows to the wellbore till the well is killed properly. A sensitivity study was done for both, kick size and kick intensity since they are considered the main contributors that affect well control prior well design and prior well killing.

2. Kick theory and kick tolerance

The effect and the behavior of a kick must be understood to successfully prevent the influx to turn into a blowout. Kicks act differently in the wellbore based on the type of the influx gas, oil or water [7]. A gas kick should be allowed to expand as it moves up on the wellbore. Uncontrolled or no expansion of the gas kick will create problems that end up with blowout. While gas migrates to the surface pressure on the surface would increase. When the well is shut in, bleed off procedure must be implemented to allow the gas to expand till killing procedure is ready to start [8]. Kick mathematics are expressed as follows:

Kick length from pit gain**:**

$$\text{Height (ft)} = \frac{\text{influx volume (bbl)}}{\text{annular capacity factor } \left(\frac{\text{bbl}}{\text{ft}}\right)} \tag{1}$$

Kick density:

$$\text{Kick density (ppg)} = \text{Mud weight (ppg)} - \frac{\text{SICP(psi)} - \text{SIDPP(psi)}}{0.052 * \text{kick length (ft)}} \tag{2}$$

where SICP= shut in casing pressure; SIDPP = shut in drill pipe pressure; MW= mud weight.

As gas migrates to surface and expands without any control, this gas influx will take so much volume in the annulus in which will definitely push large quantity of fluids out of the well and result to reduce the bottom hole pressure. Between not allowing gas to expand and allowing free expansion of the gas, well control procedures have been developed that allow a controlled expansion of the gas [9].

$$\text{Gas migration rate } \left(\frac{\text{ft}}{\text{hr}}\right) = \frac{\text{change in shut-in casing pressure (psi)}}{\text{Mud weight (ppg)} * 0.052 * \text{time for change (hr)}} \tag{3}$$

The kick tolerance is a sensitivity study to decide the maximum volume of kick that can be safely circulated without fracturing the weak formation. Below the last casing shoe sometime is the weakest point. It is essential to know if the well pressure will exceed the fracture pressure thus will cause us lost circulation and may tend to be an underground blow out [10]. Various factors influence the kick tolerance like casing shoe pressure, formation pressure, fracture gradient, mud weight in use, kick size, kick density, and circulating temperature [11].

When calculate kick tolerance it is required to figure out all vital parameters such as maximum vertical height of the influx at the casing shoe (as it is the weakest point in the open hole), well temperature, fluid density, fracture gradient, kick fluid density, predicted pore pressure and maximum allowable annular surface pressure [12]. The kick tolerance is the maximum gas volume which can be allowed to be circulated without exceeding fracture gradient of formation. Kick tolerance is the key factor to give us an indication either we can circulate the existing kick or need to look for unconventional method to control the well. Because of this, the sensitivity study was done on kick size and kick intensity since they are the major contributors that effect kick tolerance [13]. The volume for kick tolerance while well killing increases more with wellbore inclination for highly deviated section and may have more volume kick tolerance that in vertical drilling well. The volume of kick tolerance of well killing increases with the geothermal gradient [14].

Gas bubble behavior in the wellbore is influenced by both Pressure and temperature. Based on computational fluid mechanism gas bubble formation in vertical channel effected by gravity and buoyancy. As simulation indicated that gas bubble shape maintained asymmetric over development process during gas accumulation [15]. When gas influx volume increases, the decline of kick tolerance is linear. With the same pattern, as overflow depth increases, kick tolerance also shows downtrend. Thus, discovery of overflow from deep formation might provide sufficient time to control the well safely [16]. With the computing power available now and almost all rigs use computers. There is no justification of using hand and simple calculations. Accurate tools are to be used not only during well planning and designing but also while whole drilling operation to provide real time guidance for rig personal. These simulations and tools support to take accurate discussion in order not to end up with catastrophic accident [17].

3. Fractured basement reservoirs

Nowadays, the fractured basement reservoirs have become a vital natural resource to the oil and natural gas industry. There are several problems that would appear during drilling these kinds of granitic reservoir such as severe shocks, drilling vibrations, high flow rate and high network pressure. The fracture may be few micrometers of a long micro formation, or extend to thousands of kilometers as continental fault and it may be limited by a certain geological rock or layer. Moreover, the fracture does not behave as a frequently curve or straight line because of the brittle deformation process which occurs in the earth crust [18]. Due to changing the pressure direction and the rock type in the fracture, its plane is considered as a weak fragment formation. Additionally, it consists of two components: uncommon rocks surface, and the contact of them. The space between these surfaces is known as the fracture gap. Also, the fractured reservoirs formed in those surfaces and spaces are regularly classified according to the relative contribution of fractures and the rock matrix to the total production [19]. Therefore, the drilling in such geological layers is considered as a great challenging.

Conventional petroleum reservoirs are different from naturally fractured ones which they have no primary porosity and are classified as one of the petroleum reservoir types [20]. Evaluation the production fluids capacity and reserves of these kinds of basement reservoirs are considered the most difficult obstructions after discovering them [21]. Most of the drilled wells in them are often highly inclined or horizontal so as to reach the sub-vertical fault areas. In order to make them productive, the drilled wells should extend enough larger and permeable zones in the environment fractures which contain mainly the storage capacity of the reservoir. Masilah and Sab’atayn Basins are examples of productive fractured basement reservoirs located in Yemen. Hydrocarbons formed basement reservoir formation have been discovered since more than a decade ago in various fields [22].

4. Well data description

Well X is located in a Basement field north of Sab’atayn Basin NW-SE. The basin is a late Jurassic. The block started to produce 17 MBOPD since 2005 from fractured basement reservoir. The oil produced is light between 35° to 42° API. Wellbore sketch is shown in Figure 1. Details of the well equipment and components are illustrated in Tables 1 and 2. The length of the open hole section is 2080 ft with 8 1/2" diameter. Simulation will be implemented for the expected kick from this basement reservoir. Additionally, a sensitivity analysis is done in order to show the influence of the kick size and the kick density on controlling well X during exposing to kick from this reservoir.

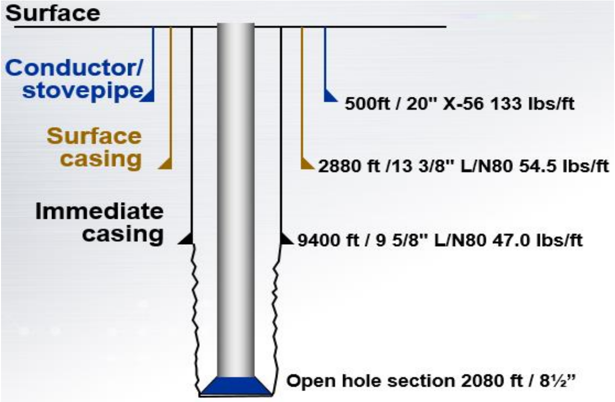

Figure 1. Well X sketch

Table 1. Drillstring and bottomhole assembly description.

Drill String Components	Section length ft	Inside Diameter in	Outside diameter in	Distance from Btm (ft)
8.5" PDC Smith Bit w float	3.0832	2.81	6.75	0.98
A675XP Motor	25.912	5.5	6 3/4	26.90
8 3/8'' Stabilizer	5.576	2.7	6 1/2	32.47
Float Sub	2.624	2.8	6 1/2	35.10
6 3/4'' Pony NMDC	9.0856	2.8	6 3/4	44.18
MWD	34.112	3.8	6 3/4	78.29
6 3/4'' NMDC	29.52	2.8	6 3/4	107.81
5'' HWDP	30.832	3.875	5.5	138.65
6-1/2" Jars	32.472	2.5	6 1/2	171.12
5'' HWDP	30.832	3	5	201.95
5'' DP	285.36	4.778	5.5	487.31
5'' HWDP	554.32	3.87	5.5	1041.63
DIBPV	2.952	3.875	6 1/4	1044.58
5'' HWDP	30.832	3.875	5.5	1075.41
Drill pipe	10407.44	4.778	5.5	11482.85

Table 2. Casing specifications and properties of well X.

Casing	Setting depth ft	Inside Diameter in	Outside Diameter in	Hole Diameter in
20" X-56 133.0 lbs/ft	500	18 3/4	20	23
13 3/8" L/N80 54.5 lbs/ft	2880	12 3/5	13 3/8	17 1/2
9 5/8" L/N80 47.0 lbs/ft	9400	8 2/3	9 5/8	12 1/4

5. Research methodology

In order to perform this research study, a Drillbench multiphase simulator that provides complete modeling of the effects of temperature, compressibility, gas solubility and hydraulics under all conditions throughout the wellbore. These effects cannot be easily included in the simpler traditional models, which basically treat all kicks as single bubble water-based mud scenario. Under static conditions, the simulations provide a profile of the insitu mud weight as well as ESD for the wellbore [23]. After the well is shut-in, the wellbore pressure is allowed to stabilize. The shut-in time is kept until the bottomhole pressure equals the pore pressure and the influx has stopped. This was selected from the shut-in period drop down list. Circulation rate was defining the pump rate when circulating the kick. Table 3 shows the simulation parameters for Engineer's method [23]. In general, the pit alarm level indicates as the kick is detected at surface. When the alarm is activated, the simulator commences shut-in procedure. The shut-in procedure was performed based on the operational times given at the Surface equipment group in the Input Parameter section. A flow check is performed as soon as the pumps are off. The flow check continued until volume increases in the pit is achieved. Table 4 summarizes the simulation process for the Engineer's method.

6. Simulation results and discussion

Multiphase Kick behavior and tolerance are studied and investigated in well X drilled to produce from the highly fractured basement reservoirs using the Drillbench multiphase simulator as shown in Figures 2 through 10 and Tables 3 through 5. The effect of reservoir would appear through changing the kick size 10, 50, and 80 bbls. The pit gain when the well kick 10 bbl and the kick intensity is 0.5 ppg (Figure 2). The pit gain remains 10 bbl till the 70th minute after that start to increase. Further, the pit gain is increasing as the kick is circulated out and reaches maximum when the top of the gas kick arrives to the surface with volume of 21 bbl in 120 minutes. When the pit gain decreases the gas kick is starting to leave the well. The gas circulated out completely and kill mud is displace in both drill pipe and annulus in 190 minutes. The choke pressure plotted in Figure 3 shows that at 10th minute pit gain is 10 bbl. From 10th to 40th minutes well is shut-in and pressure stabilized at 310 psi. Well killing starts at 40th minute and reaches the highest surface pressure of 660 psi. Pressure starts to decrease after the influx is flowing to surface and all gas babbles has been circulated out. The well is completely killed and full of kill mud in 220 minutes.

Table 3. Simulation parameters for Engineer's method.

Pre kick circulation time	10 minutes
The pit alarm level	50 bbl
Shut-in period	30 minutes
Circulation rate	100 gallons/min
Circulation mode	Constant bottomhole pressure
Various kick intensity	0.50 ppg – 1 ppg – 1.5 ppg
Various kick volume	10 bbl – 50 bbl - 80 bbl
Safety margin	100 psi
Simulation method	Engineer's method

Table 4. Simulation process.

1 Pull out of hole.
2 When kick is detected shut-in the pump.
3 Continue simulation. The simulation activated till the program shows that the pump is off.
4 Close the BOP. Simulation runs till it shows that BOP is closed.
5 Shut-in time recorded.
6 Open choke.
7 Turn on the pump.
8 Circulate the kick out.

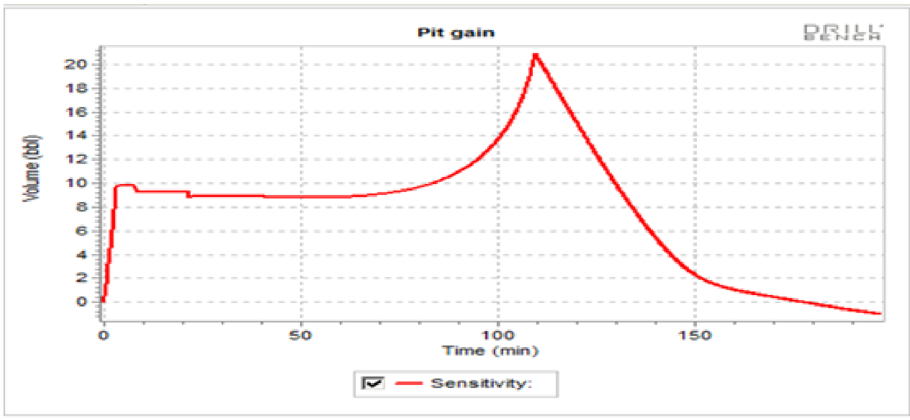

Figure 2. Pit gain of 10 bbl vs .5 ppg kick intensity sensitivity analysis profile

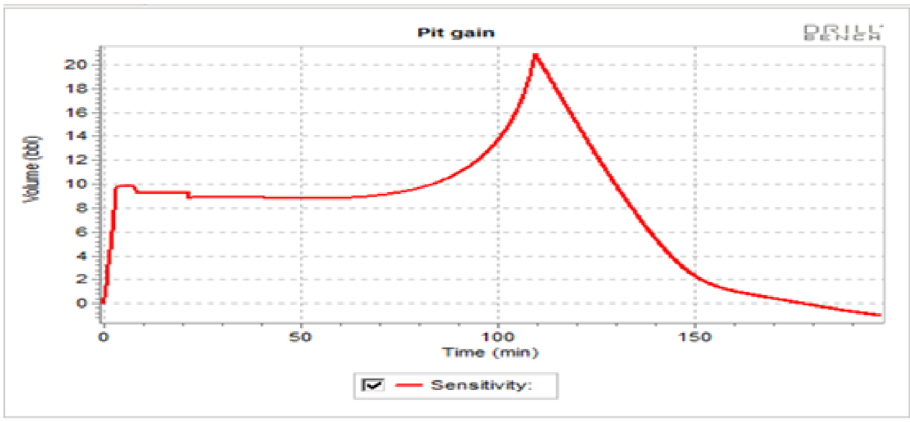

Figure 3. Choke pressure at 10 bbl pit gain vs .5 ppg kick intensity sensitivity analysis profile

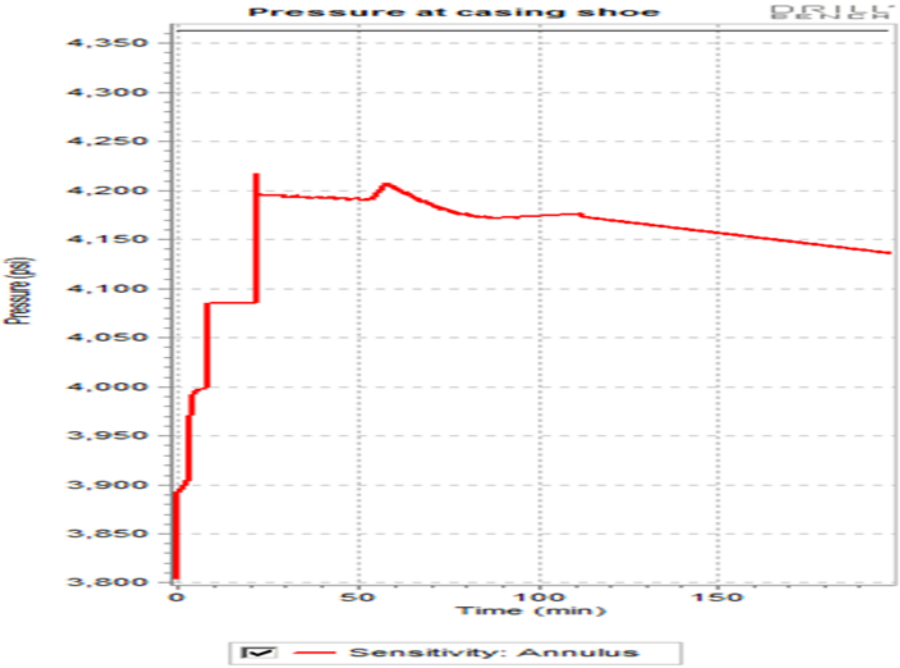

Figure 4. Pressure at casing shoe at 10 bbl pit gain vs .5 ppg kick

Figure 4 shows the behavior of the pressure while the influx travels in the annulus in the kill procedure. As kick inters the annulus pressure increases as influx moves up, with maximum pressure at the shoe is 4210 psi. After that pressure reduces as it passes above the shoe. A constant decrease as the kill weight mud is being pumped down the drill pipe. Moreover, Figure 5 shows the pit gain when the well kicks 50 bbl and the kick intensity increased to be 1 ppg. The pit gain remains 50 bbl since the well is shut-in. The pit gain is increasing as the kick is circulated out and reaches maximum when the top of the gas kick arrives to the surface with volume of 60 bbl in 120 minutes. When the pit gain decreases the gas kick is starting to leave the well. The gas circulated out completely and kill mud is displace in both drill pipe and annulus in 220 minutes. The choke pressure in Figure 6 shows that when the well kicks 50 bbl and kick intensity increased to 1 ppg. From 10th to 40th minutes well is shut-in and pressure stabilized at 440 psi. Well killing starts at 40th minute and reaches the highest surface pressure of 1230 psi. Pressure starts to decrease after the influx is flowing to surface and all gas babbles has been circulated out. The well is completely killed and full of kill mud in 220 minutes. Figure 7 shows the behavior of the pressure while the influx travels in the annulus in the kill procedure. As kick inters the annulus pressure increases as influx moves up with maximum pressure at the shoe is 4580 psi which it above the fracture pressure. After that pressure reduces as it passes above the shoe. A constant decrease as the kill weight mud is being pumped down the drill pipe. The casing shoe pressure decreases until the kill mud enters the annulus. The casing shoe pressure drops because of the higher static pressure from the kill weight mud in the annulus. Figure 8 shows the pit gain when the well kick 50 bbl and the kick intensity is increased to be 1.5 ppg. The pit gain remains 50 bbl since the well is shut-in. The pit gain is increasing as the kick is circulated out and reaches maximum when the top of the gas kick arrives to the surface with volume of 59 bbl in 70 minutes. When the pit gain decreases the gas kick is starting to leave the well. The gas circulated out completely and kill mud is displace in both drill pipe and annulus in 220 minutes.

The choke pressure constructed in Figure 9 shows that when the well kicks 50 bbl and kick intensity increased to 1.5 ppg. From 10th to 40th minutes well is shut-in and pressure stabilized at 640 psi. Well killing starts at 40th minute and reaches the highest surface pressure of 1400 psi. Pressure starts to decrease after the influx is flowing to surface and all gas babbles has been circulated out. The well is completely killed and full of kill mud in 220 minutes. Figure 10 shows the behavior of the pressure while the influx travels in the annulus in the kill procedure. As kick inters the annulus pressure increases as influx moves up with maximum pressure at the shoe is 4730 psi which it above the fracture pressure. After that pressure reduces as it passes above the shoe. A constant decrease as the kill weight mud is being pumped down the drill pipe. The casing shoe pressure decreases until the kill mud enters the annulus.

Table 5. Sensitivity study various kick sizes vs different kick intensities.

WBM	10 bbl pit gain vs 0.5 ppg kick intensity	50 bbl pit gain vs 1 ppg kick intensity	50 bbl pit gain vs 1.5 ppg kick intensity	80 bbl pit gain vs 0.5 ppg kick intensity
Maximum pump pressure, psi	510	750	900	590
Stabilized shut-in drill pipe pressure, psi	180	340	500	180
Maximum choke pressure, psi	660	1230	1400	1640
Stabilized shut-in choke pressure, psi	310	440	640	400
Maximum casing shoe pressure, psi	4210	4580	4730	4490

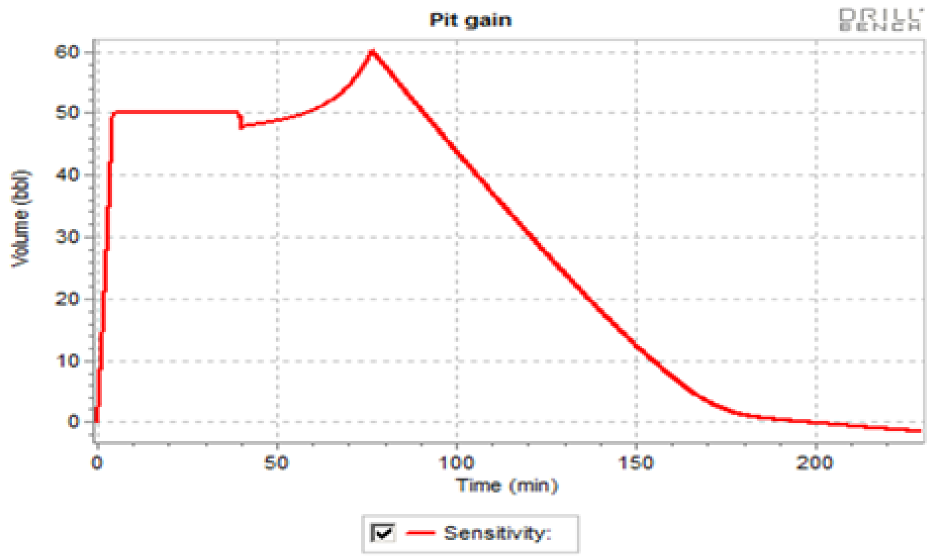

Figure 5. Pit gain profile at 50 bbl vs 1 ppg kick

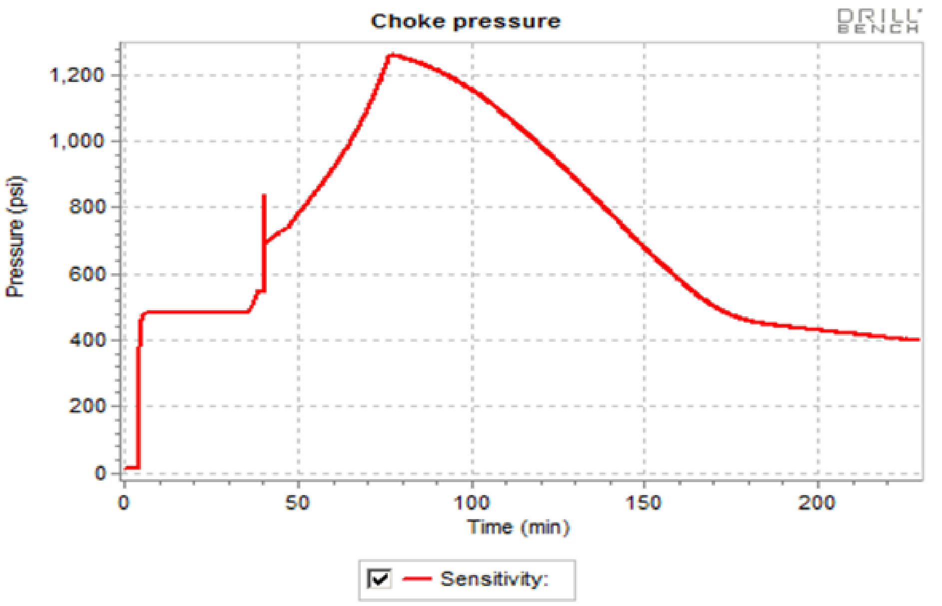

Figure 6. Choke pressure profile at 50 bbl pit gain vs 1 ppg kick intensity

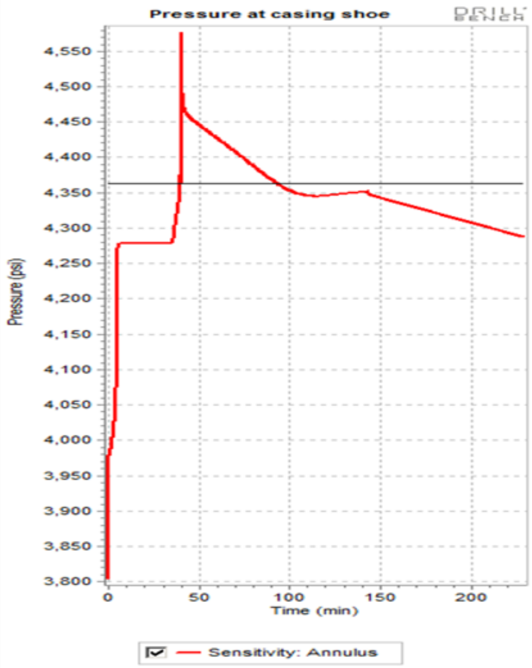

Figure 7. Casing shoe pressure at 50 bbl pit gain vs 1 ppg kick.

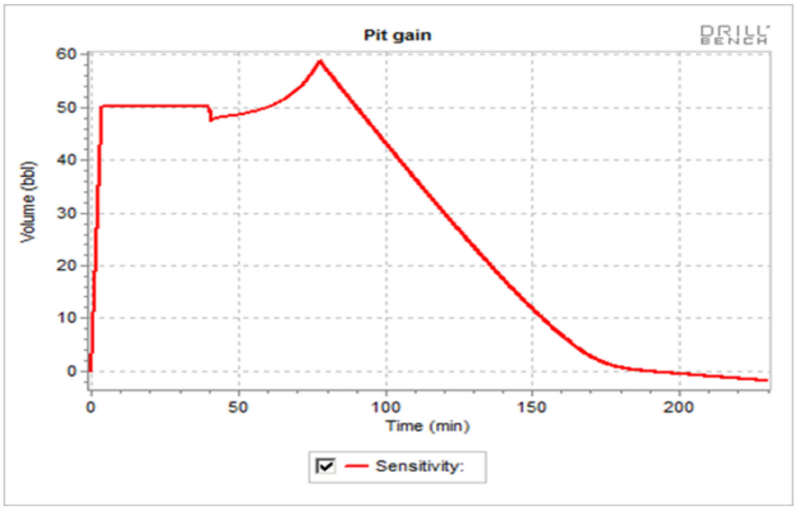

Figure 8. Pit gain profile at 50 bbl pit gain vs 1.5 ppg kick intensity.

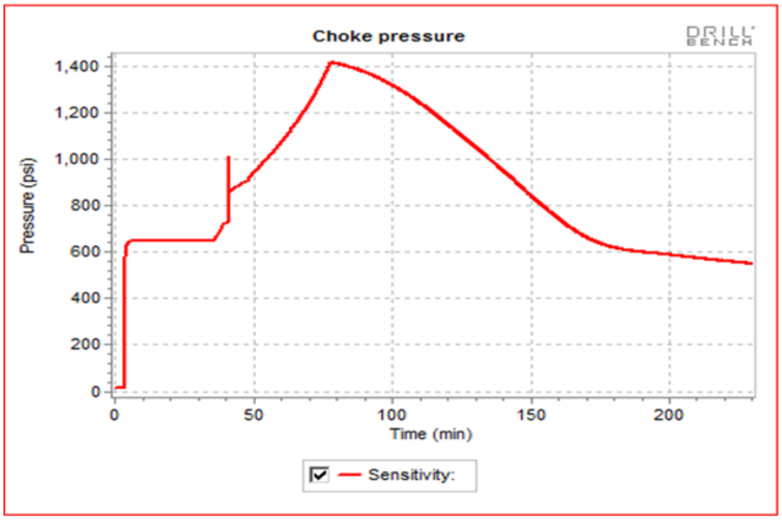

Figure 9. Choke pressure profile at 50 bbl pit gain vs 1.5 ppg kick intensity.

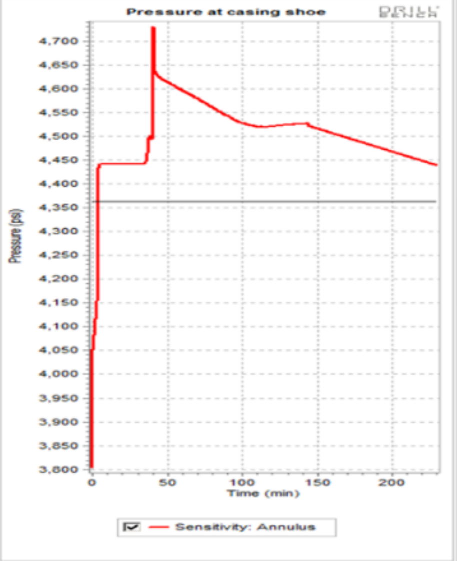

Figure 10. Casing shoe pressure profile at 50 bbl pit gain vs 1.5 ppg kick intensity

Finally, the kick size highly influences the pressure behavior while the fluid migrates from bottom hole to the surface (Table 5). The bigger the size of kick the higher pressure of the influx. When the pit gain was 10 bbl pressure profile was 510 psi pump pressure, 660 psi choke pressure and 4210 psi casing shoe pressure. When the kick size is 50 bbl and kick intensity is 1 ppg the pump pressure increased to 750 psi, choke pressure increased to 1230 psi and the casing shoe is 4580 psi. As expected that the more kick intensity the bigger effect will be. When the kick intensity is 1.5 ppg the pressure behaviour changed accordingly and increased to 900 psi pump pressure, 1400 psi choke pressure and 4730 psi casing shoe pressure. If the kick is 80 bbl a remarkable pressure increases is noticed 590 psi pump pressure, 1640 psi choke pressure and the casing shoe pressure increased reaches maximum pressure to 4490 psi.

7. Conclusions and recommendations

This research work has successfully produced a complete swab kick model and proven that the well control simulation is a real time powerful tool to assess the impact of kick intensity and kick volume on casing shoe pressure, bottomhole pressure, and choke pressure. It has examined and developed a comprehensive understanding of kick behavior from the time when the kick flows to the wellbore till the well is killed sufficiently and safely. Consequently, kick tolerance was considered a key factor that gave an indication either to circulate the existing kick or need to look for unconventional method to control the well. Investigations show that as the kick is detected and circulated out of the well in a controlled manner while maintained constant bottomhole pressure, an increase was observed in pit gain, casing shoe pressure, choke pressure, and drill pipe pressure. It was proven that kick size and kick intensity have major effects on well control. The bigger the kick size and kick intensity result in higher pressure profile. Basement reservoirs has intensive fractured and pressurized network, the size of kick tends to be bigger than the conventional sand stone reservoirs. As a result, Basement reservoirs require more attention while circulating the kick to the surface and even minor kick tolerance needs to be taken into consideration.

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To whom correspondence should be addressed: Eng. Osama Sharafaddin, Petroleum-Gas University of Ploiesti (UPG), Ukraine, Romania, E-mail: osharaf2015@gmail.com