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Well Control Modeling – Software Comparisons with Single Bubble Techniques in a Vertical Well

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Recent advances in well control modeling simulators have incorporated multiphase flow concepts into the modeling of well control events. In the past, the "single bubble" theory has been used for worst-case calculations related to kicks. The concept behind this technical writing is to compare the results from the old techniques of the single bubble theory with the new modern simulations. The expanded use of oil-based muds in recent times has also raised interest related to the manner in which many kicks react when compared to the previously described single bubble calculation methods. The intent is to provide the reader with knowledge of how the single bubble theory and well control simulations compare and what may be expected when an actual kick circulation occurs.

Introduction

Well control modeling has seen significant improvement in recent years with the introduction of multiphase flow simulators. These tools, when coupled with experience, can be very useful to the well control or drilling engineer when planning a wellbore or to assist with well control remediation operations. The techniques used in the past have referenced the consideration of a "single bubble" within the wellbore. This consideration makes the calculation process for pressure predictions more feasible to hand calculations or spreadsheets. This calculation method simplifies the scenario and makes some basic assumptions to facilitate the calculation process. However, this is often not a true reflection of what has occurred within the wellbore, and therefore can result in poor predictions of what is actually witnessed at the wellsite.

This document is intended to provide a comparison of the modern multiphase modeling with the previously published techniques involving the use of the single bubble concept. Personnel at the wellsite are the frontline of defense for well control and are the target audience, along with drilling and well control support personnel. The discussion within this document is intended to provide those personnel with insight into the pressure reactions during a well control event. It is necessary to understand how the single bubble theory compares with the modern well control simulations in order to have a clear understanding of what to expect when circulating out a kick. In some cases, an unexpected pressure response in a well control event can lead to poor remedial actions. This can lead to complications within the well control remedial operations, and even further escalation of an event. It is critical that personnel involved in well control efforts truly understand what has occurred and what additional items to expect during a well control event.

This comparison is also intended to provide the drilling engineer with a better understanding of the pressure responses during a kick. In many cases, decisions are made based on the divergence of "expected" pressure reactions compared to what actually occurs at the well. Well control simulation software is designed to provide a more realistic expectation of pressure response than the simple single bubble theory techniques.

Review of Single Bubble Theory

Many well control calculations use the theory of a single bubble. This suggests that the gas enters the wellbore as a singular component and is not dispersed within the drilling fluids in the wellbore. This allows for simplification of various assumptions and allows for hand calculations to be completed using simplified equations.

The following are the equations used for the purpose of this study. These equations can be located in *Firefighting and Blowout Control* from Abel, et al. The equations allow for the calculation of the pressure at the top of the gas bubble at any Depth of Interest (DOI) within the well. For the purpose of this study, the Driller's Method and Engineer's Method have been included. The equations used are as follows:

Driller's Method – Pressure at Depth of Interest

$$P_{DOI} = \frac{B}{2} + \sqrt{\left(\frac{B}{2}\right)^2 + C}$$

$$B = BHP - (0.052)(\rho_m)(TVD_{Kick} - TVD_{DOI})$$

$$C = \frac{(0.052)(\rho_m)(BHP)(Vol_{kick})}{ACF}$$

This equation does not account for the hydrostatic pressure of the gas or the effects of temperature and z-factor.

The following equation can be used to account for these parameters:

$$P'_{DOI} = \frac{B'}{2} + \sqrt{\left(\frac{B'}{2}\right)^2 + C'}$$

$$B' = BHP - [(0.052)(\rho_m)(TVD_{Kick} - TVD_{DOI})] - P_g$$

$$C' = \frac{(0.052)(\rho_m)(BHP)(Vol_{kick})(T_{DOI})(Z_{DOI})}{(ACF)(T_b)(Z_b)}$$

Engineer's Method – Pressure at Depth of Interest

$$P_{DOI} = \frac{A}{2} + \sqrt{\left(\frac{A}{2}\right)^2 + E}$$

$$A = BHP + (0.052)[(L)(\rho_k - \rho_m) - (\rho_k)(TVD_{Kick} - TVD_{DOI})]$$

$$E = \frac{(0.052)(\rho_k)(BHP)(Vol_{kick})}{ACF}$$

The above equation does not account for the hydrostatic pressure of the gas or the effects of temperature and z-factor.

The following equation can be used to account for these parameters:

$$P'_{DOI} = \frac{A'}{2} + \sqrt{\left(\frac{A'}{2}\right)^2 + E'}$$

$$A' = BHP + (0.052)[(L)(\rho_k - \rho_m) - (\rho_k)(TVD_{Kick} - TVD_{DOI})] - P_g$$

$$E' = \frac{(0.052)(\rho_k)(BHP)(Vol_{kick})(T_{DOI})(Z_{DOI})}{(ACF)(T_b)(Z_b)}$$

Where:

$$P_{DOI} = Pressure\ at\ the\ top\ of\ a\ gas\ buble\ at\ the\ DOI$$

$$BHP = Bottom\ Hole\ Pressure$$

$$\rho_m = Density\ of\ original\ mud\ in\ the\ well$$

$$\rho_k = Density\ of\ kill\ weight\ mud$$

$$TVD_{Kick} = True\ Verticle\ Depth\ of\ the\ kick\ formation$$

$$TVD_{DOI} = True\ Verticle\ Depth\ of\ the\ DOI$$

For the purpose of this study, the following key points relevant to the single bubble theory should be identified:

- The calculations do NOT account for any dispersion of the kick effluent into the drilling fluids.
- The calculations do NOT account for gas migration within the drilling fluid column.

These assumptions are important to note as they are markedly different from the transient well control calculations within the software.

It should be noted that these simplifying assumptions have always been intended to provide the engineer with a worst-case pressure profile. The understanding has always been that an actual kick would have a pressure profile that is less severe than the calculated peak pressure for a single bubble kick. The following sections of this study demonstrate that this point is still valid and the software simulation peak casing pressure values are less than those predicted with the single bubble equations.

Kick Study Discussion

There are many factors associated with a kick that can impact the intervention efforts. It has always been desirable to understand how a kick will react so that personnel at the rig can respond appropriately. It is also important that personnel recognize any unexpected complications to assist with deviations to previously planned operations, as the need arises. Understanding the pressure response to a kick is critical for a successful resolution.

The well control software is commonly misunderstood when attempting to compare it to simplified calculations. The software is transient and accounts for other associated parameters within the circulation process including (but not limited to) the following:

- Frictional pressure through the choke and choke line
- Kick and drilling fluid solubility and interactions
- Temperature effects on the kick and drilling fluids
- Kick migration within the drilling fluid column
- Impacts of time on all parameters

These additional inputs can complicate the process and make it difficult for the unfamiliar personnel to compare the software to the standard single bubble results. Experience in dealing with well control events can also play a vital role in the determination of these various parameters within a reasonable range for actual field operations. These factors can complicate the process, but are the parameters that are intended to give the software simulations a most realistic response to an event.

Given these distinct differences in the two techniques, it was desired to limit the possible influences of this within this study. In order to accomplish this, the following considerations were noted:

- The shut-in time for the simulations was minimal and not realistic to what would happen at the rig. This was completed to show a more true comparison to the single bubble calculations.
- The influx rate was maximized for the simulations to attempt to provide as close to a single bubble scenario as possible, and limit dispersion of gas into the drilling fluid.
- The drill string in the simulations consisted only of drillpipe. This is to be consistent with the assumptions within the single bubble calculations of a constant geometry throughout the well.
- A "normal" temperature profile was used for the simulations of 1.0 °F/100'.

For reference purposes, the wellbore and reservoir parameters used for this study have been included in the table below. The desire was to be as consistent as possible for a true comparison between the two calculations methods.

Description	Value	Comments
Reservoir Pressure	5,460 psi	A calculated 0.5 ppg kick intensity
Reservoir Depth	9,990' – 10,000'	Assumed
Kick Fluid	Dry Gas	Assumed
Drilling Fluid	10.0 ppg WBM and OBM	WBM and OBM used for comparison
Circulation Rate	2.0 bbl/min	Assumed for simulations
Kick Size	25 and 100 bbls	Assumed for comparison
Kick Injection Rate	5 bbl/min	Manipulated in the software to resemble single bubble
9 5/8" Casing	ID = 8.535"	Assumed.
Open Hole	ID = 8.500"	Assumed
Casing Shoe Depth	5,600'	Assumed

The relatively shallow depth used for this comparison allowed for a small deviation on the software calculated mud density at the kick reservoir depth. Deeper HPHT type well configurations lend to a greater variance between the simulated Bottom Hole Pressure (BHP) and the conventional linear calculated value using TVD and mud density. This deviation can be significant, depending on the given well parameters. The intent for this study was to minimize the variance and get a better relative comparison to the two presented methods of calculation.

The initial shut-in of the well provides an initial perspective on the variance of the calculated values. The following table presents the TVD/MD of the top of the kick for each kick volume case. As can be noted, there is a substantial difference in the location of the top of the kick fluids when compared to the calculated single bubble value.

25 bbl Kick		
Kick Size	**Top of Kick Fluid**	**Comments**
25 bbl – Calculated	9,455'	Calculated as single bubble
Simulations		
25 bbl – 10.0 ppg OBM	9,050'	Software
25 bbl – 10.0 ppg WBM	8,720'	Software

100 bbl Kick		
Kick Size	**Top of Kick Fluid**	**Comments**
100 bbl – Calculated	7,821'	Calculated as single bubble

Simulations		
100 bbl – 10.0 ppg OBM	6,610'	Software
100 bbl – 10.0 ppg WBM	6,260'	Software

This denotes why there is a marked deviation in the peak surface pressures calculated from the simulated values. There is also a definitive difference in the volume pumped to have the initial gas (top of the kick) reach the surface on the various methods.

The software predicted top of the kick shows that the kick effluent is still dispersed within the drilling fluid, even though the kick is injected rapidly into the wellbore. This is coupled with active gas migration throughout the circulation.

Simply based on this information, it could be concluded that the following are likely to occur during the circulation operations:

1. The maximum surface pressure calculated with the provided formulas will be greater than that from the simulations because there is a dispersion of the gas within the drilling fluid with the software.
2. The peak pressure will likely occur earlier in the circulation than the predicted value using the single bubble calculations, as the top of the kick fluid is already higher in both simulation scenarios upon the initial shut-in of the well.

When the data from the simulations is plotted with the calculated values, these points are clearly realized. The charted data has been included at the end of this document for further reference. This is consistent with both the Driller's and Engineer's Methods. The peak casing pressure and gas to the surface occurs before the calculated values would suggest with the simulation in the WBM and OBM. The deviation is much greater with the WBM simulations than that of the OBM. The OBM simulation was closer with respect to volume on when the kick reached the surface, but was still at a reduced pressure. According to the software, the kick in the OBM system is less dispersed and reacts more consistently with the single bubble theory. The kick in the WBM was more dispersed and also appeared to be influenced by migration, and thus less similar to the react as predicted with the single bubble calculations. This was behavior was anticipated, and was further supported by the simulation results.

The data from the Driller's Method kill simulations is plotted and compared to the calculated single bubble values in *Figure 1*. One significant take-away from this plot is the volume pumped when the kick initially reaches the surface. This occurs much sooner than would be expected from the simplified calculations. This may be of significant importance as crews would not likely expect the peak gas to occur until later within the circulation process. This "early" arrival of the kick may also bring into question the location of the kick zone and possibly the point of circulation within the wellbore. From this data, further investigation may be warranted to determine the sensitivity of a kick in a WBM to various fluid parameters. Knowledge of this sensitivity may be useful for the determination of when to expect peak gas at the surface. However, the point should still be made that the simulations indicate that gas to surface and peak casing pressure would occur prior to the calculated values using the single bubble techniques.

When attempting to examine the 100 bbl kick scenario, it must be mentioned that there appeared to be some instability within the software for the WBM scenario. Significant gas volumes can lend to this instability in certain configurations. However, the data has been included for the purposes of this document. The data for the 100 bbl kick can be located in *Figure 2* below.

This graph shows that the gas will reach the surface prior to the anticipated pumped volume from the single bubble calculations. This scenario indicates a greater dispersion within the OBM system due to the time required to inject the larger volume of kick fluids. The top depth of the kick for each scenario was included in the previous table as well. The 100 bbl scenario for the corrected single bubble peak casing pressure value matches well with the simulation results for the WBM. The uncorrected value is still deemed to be more conservative than the software suggests.

The same comparison was made with a 25 bbl kick using the Engineer's Method for circulation. The conclusions from this data were very similar to those from the previous Driller's Method discussion. This data is detailed in *Figure 3* in the following section. No 100 bbl kick was included for the Engineer's Method for the purpose of this study.

All of the values within this report are calculated or simulated. There is no actual data set to compare to for this scenario. However, this software has been used in the past to compare actual rig data from a well control event to the software predictions. The software predictions match extremely well with the recorded data. This is important as it adds confidence to the accuracy of the simulated values. Based on this past experience, the simulated data is expected to be comparable to what an actual kick would resemble. This software has been used by BE personnel to examine actual kick data in the past and has performed favorably.

Kick Conclusions

The following are some general conclusions that have been reached regarding the study of kick simulation software and single bubble theory:

- The maximum casing pressure prediction from the single bubble theory appears to be a conservative value for the anticipated casing pressure during well control circulation operations in both WBM and OBM systems. This can be useful to the drilling or well control engineer when planning various operations.
- Field personnel may experience gas to the surface prior to the calculated values in the single bubble techniques. Gas arrival at the surface is relative to the dispersion within the drilling fluids so early arrival does not necessarily suggest a shallow kick zone or communication point.
- When the transient (time) component is added to the system, simplified calculations like the single bubble predictions diverge from the software predictions.
- The simulated kicks in an OBM provided a lower resultant casing pressure than in WBM. The software appears to attribute this to migration of the gas within the fluid system.

This study has prompted the need for further discussion of other parameters that are also associated with the kick calculations from the single bubble theory. Further investigation of several topics will be included in future technical documents.

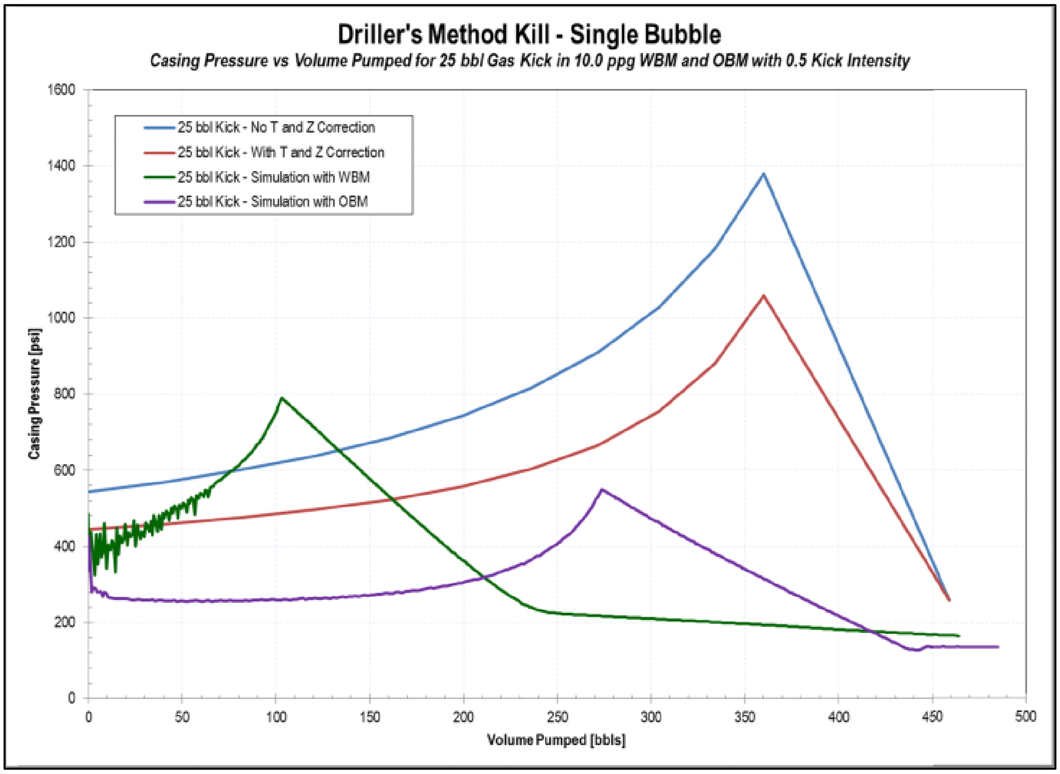

Figure 1 – Driller's Method Comparison for 25 bbl Kick Volume

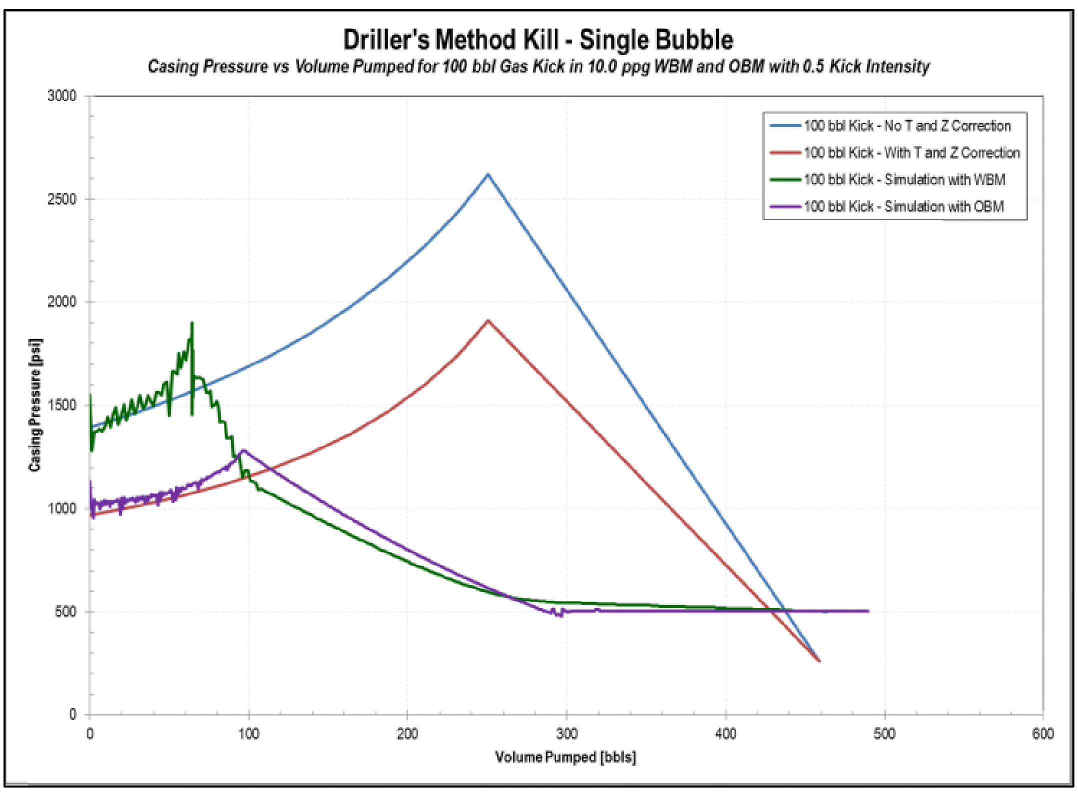

Figure 2 – Driller's Method Comparison for 100 bbl Kick Volume

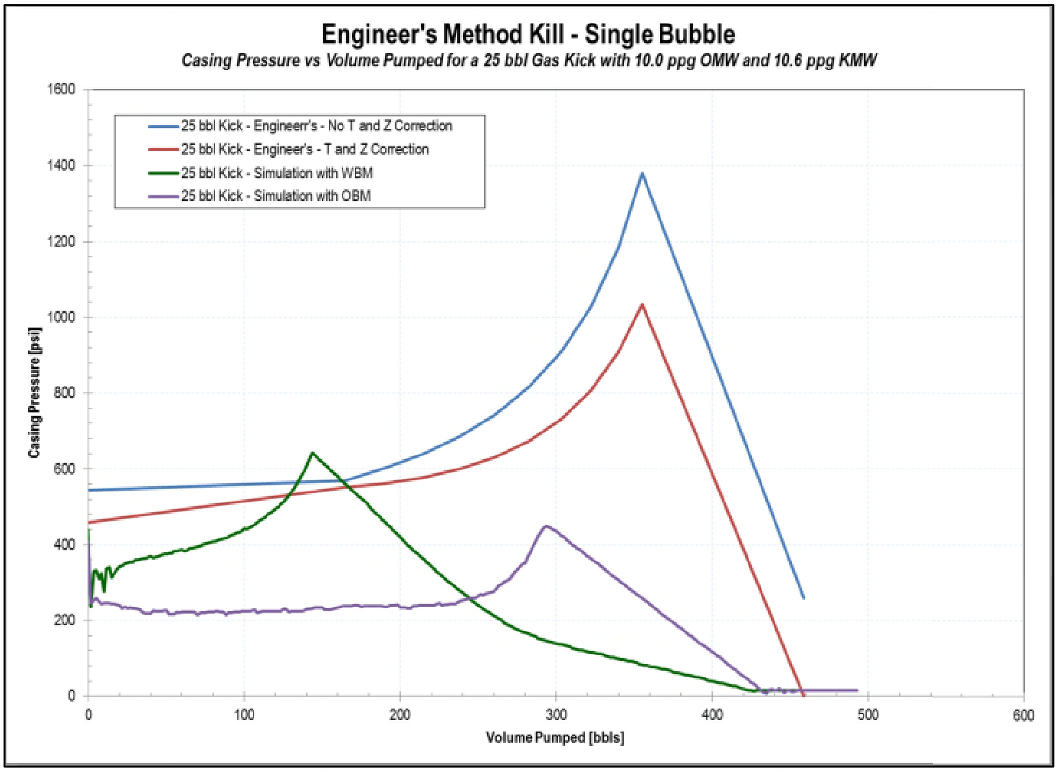

Figure 3 – Engineer's Method Comparison for 25 bbl Kick Volume