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USE OF A TRANSIENT MODEL FOR STUDYING KICK MIGRATION VELOCITIES AND BUILD-UP PRESSURES IN A CLOSED WELL

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ABSTRACT

The objective of the paper is to show that using pressure build-up curves for estimating kick migration velocities can be unreliable. This will be demonstrated by using a transient flow model where different flow patterns including suspended gas are considered. Suspended gas will occur in Non-Newtonian drilling fluids. This can also be the reason why there is reported large discrepancies in literature about what the gas kick migration velocities can be.

A transient flow model based on the drift flux model supplemented with a gas slip relation will be used. The model will be solved by an explicit numerical scheme where numerical diffusion has been reduced. Different flow patterns are included i.e. suspended gas, bubble flow, slug flow and transition to one-phase gas. Kick migration in a closed well will be studied to study how pressure build-ups evolve. A sensitivity analysis will be performed varying kick sizes, suspension limits and changing the transition intervals between the flow patterns.

It is seen in literature that the slope of the pressure build-up for a migrating kick in a closed well has been used for estimating what the kick velocity is. It has been reported earlier that this can be an unreliable approach.

In the simulation study, it is clearly demonstrated that the suspension effect will have a significant impact of reducing the slopes of the pressure build-ups from the start of the kick onset. In some severe cases, the pressure builds up but then it reaches a stable pressure quite early. In these cases, the kick has stopped migrating in the well. However, in the cases where the kicks are still migrating, it seems that the bulk of the kick moves at the same velocity even though the degree of suspension is varied and gives different slopes for the pressure build-up. Hence, it seems impossible to deduce a unique gas velocity from different pressure build-up slopes. However, abrupt changes in the slope of the pressure build-up indicate flow pattern transitions.

Keywords: gas kick migration velocities, pressure build-up in closed well, gas suspension effects.

NOMENCLATURE

BOP	Blowout preventor
WHP	Wellhead pressure (just below BOP)
BHP	Bottomhole pressure
S	Gas migration velocity
K	Flow parameter in the gas slip relation

1. INTRODUCTION

There has been some confusion in literature about what are the real gas kick migration velocities. This was first pointed out in [1]. The discrepancy was that in small scale experiments and full-scale test wells, the gas velocity was estimated to be around 100 ft/min while field estimates indicate gas rise velocities of only 15 ft/min. This discrepancy is still around as seen in [2,3] Recent fields observations from pressurized mud cap drilling operations seem to indicate a very low gas migration velocity [3]. However, it is not clear from literature how the gas velocities were estimated for these field observations.

One should also note that simulators being used for kick simulation have typically been validated against small scale experiments and full-scale test wells. Transient kick models typically use correlations from literature for how the gas migration velocity would be for bubble and slug flow regime [4]. Hence, the simulators will typically predict a much larger kick migration velocity compared to the low values reported from the field.

It is also important to be aware of that a gas kick will behave differently when comparing a Newtonian fluid (water) vs. a Non-Newtonian drilling fluid. The most important difference is that parts of the gas kick can become suspended in a Non-Newtonian drilling fluid and in some cases, it can stop migrating completely. Small scale experiments reported in [5] indicated this. This was further discussed in [1]. Here also field tests demonstrating the suspension effect were included. These field tests were also later published in [6]. The main conclusion in [1] was that for gas concentrations larger than 10 %, the gas kick will migrate with a velocity of around 0.5 m/s in a Non-Newtonian fluid. However, the migrating kick will leave a trail of suspended gas bubbles in the well that will alter the compressibility of the complete fluid system which again will have large impact on the pressure build-up curves in a closed well. It was concluded that a misinterpretation of the pressure build-up will lead to the prediction of very low gas migration velocities.

One can note that another difference that was pointed out in [1,5] was that the transition from bubble flow to slug flow takes place at a lower gas volume concentration for Non-Newtonian fluids (10 %) compared to what is typically seen in literature when considering a Newtonian fluid (20%) [4]. A kick migration velocity of around 0.5 m/s is typically achieved when using the slug flow model.

There has been attempts on including the suspension effect in kick simulators. In [7], the effect was included by introducing a correlation for the gas concentration value that would cause the gas bubbles to be trapped by the drilling fluid. However, no details were given about the form of this. In this paper, we will define this concentration value as the suspension limit. If the gas concentration is lower than this, the gas will be trapped in the drilling fluid.

Gas kicks entering the riser can lead to unloading of the riser. However, the gas suspension effect also has large impact on whether this will occur or not. Simulation studies demonstrating the effect of gas suspension in this situation were presented in [8].

In this paper, we will use the transient flow model developed in [8] to study the pressure build-up when a kick migrates in a closed well for various kick sizes and suspension limits. The model includes both the bubble and slug flow regime and it will also be demonstrated what would be the effect of shifting the transition interval from bubble to slug flow. The work is a continuation of the simulation study performed in [9]. For more details about the results presented here one can also consider [10]. In the next section, a brief introduction is given to the flow model being used with focus on describing the gas slip model.

2. FLOW MODEL

The fully transient drift flux model has been adopted which is composed of two mass conservation laws for the two phases present. A mixture momentum equation is used. A gas slip model must be supplied which will be discussed in more detail later. The mathematical formulation of the conservation laws can e.g. be seen in [8,10]. This model has been shown to be hyperbolic describing propagation of sonic waves and a gas mass fraction wave.

For the liquid and gas density, the simple models presented in [9,10] were used. The friction model is described in [10] although the friction is of minor importance for the simulation cases studied here.

2.1 Gas Slip Model

The general gas slip relation is given by the following formula:

$$v_g = Kv_{mix} + S = K(\alpha_l v_l + \alpha_g v_g) + S \quad (1)$$

Here v represents velocity and the subscripts l and g denote liquid and gas phase. The phase volume fraction of each phase is represented by α and $\alpha_l + \alpha_g = 1$. K and S are flow regime dependent parameters where S will represent the gas migration velocity in a closed well.

In the simulation cases to be represented later, the suspension limit is defined as a percentage. If e.g. the suspension limit is set to 3 %, it means that $\alpha_{g,susp} = 0.03$. If the gas volume fraction is lower than this, the gas bubble will be trapped by the drilling fluid, and one will use the gas slip relation corresponding to no slip conditions using $K = 1$ and $S = 0$.

The bubble flow regime is assumed to take place for gas volume fractions in the interval $[\alpha_{g,susp} + 0.02, 0.2]$. Here $K = 1$ and S was modelled using Harmathy's equation [11]:

$$S = 1.53\left[\frac{g(\rho_l - \rho_g)\sigma}{\rho_l^2}\right]^{0.25} \quad (2)$$

Here, g is the gravity constant and ρ with subscripts represent phase densities. The interfacial tension σ was set to 0.0772 N/m. S will typically have a value varying around 0.2 m/s as e.g. shown in [9].

For slug flow, we adopted the model presented in [12]. Here $K = 1.2$ and the gas migration velocity S is defined by:

$$S = 0.35\sqrt{\frac{g(\rho_l - \rho_g)d_{out}}{\rho_l}}\left(1 + \frac{0.29 d_{in}}{d_{out}}\right) \quad (3)$$

Here d_{out} and d_{in} refer to the outer and inner diameter of the annulus. The typical value for S would be around 0.5 m/s or slightly larger as shown in [9]. The model for S was used for gas volume fractions in the range [0.25,0.9] while the K value was kept equal to 1.2 for gas volume fractions in the range [0.25,0.7]. K was reduced to 1.0 for gas fractions in the interval [0.7,0.8] using linear interpolation. S was reduced to 0 m/s for gas fractions in the interval [0.9,1.0]. Also note that linear interpolation was used for the K and S values for the transition interval between suspended gas and bubble flow: $[\alpha_{g,susp}, \alpha_{g,susp} + 0.02]$. This was also used for the transition interval between bubble and slug flow: [0.2,0.25]. The latter transition interval can easily be moved to take place for lower gas volume fractions if one wants to mimic that slug flow takes place for gas volume fractions larger than 0.1 when considering Non-Newtonian fluids. To introduce smooth transition zones for the K and S parameters between the different flow regimes is important for the numerical robustness.

2.2 Numerical Scheme

The well will be discretized into a certain number of cells and then an appropriate numerical scheme must be used to progress the solution forward in time. Here, the explicit AUSMV scheme has been used. A short description of the scheme is given in [8] where it was used to study the effect of gas suspension on riser unloading. More details about how the fluxes between the cells shall be calculated can be found in [13]. In order to reduce numerical diffusion, the slope limiter concept has been used [14]. For the boundary cells at inlet and outlet of the well, the slope limiters have usually been just copied from the neighbor cells. One typically uses slope limiting for phase densities, gas volume fraction and pressure.

However, it was seen in [10,15] that for the scenario with gas migrating in a closed well, some mass conservation problems could occur in some cases. The problem was resolved by setting the slope for the gas volume fraction to zero at both the inlet and outlet boundary cell. This seemed to yield the best numerical results.

For the boundary treatment, one need to distinguish between open and closed well conditions. A description of how this can be done is given in [15].

3. SIMULATIONS

In the following, a 4000-meter deep vertical well will be considered. A 12 ¼" x 5" geometry is assumed from bottom to top. For the 12 ¼" hole section, the kick tolerance limit is often set such that if an 8 m^3 kick volume cannot be handled safely, the planned section has to be shortened. Hence, we have chosen to focus on kick volumes: 4, 8 and 12 m^3.

The well will be filled with water such that there will be only free gas present. The kick will be introduced at the bottom of the well and then the well will be closed in on top and the kick will migrate to surface causing pressure build-up in the well. The number of cells used in the discretization was 50. Slope limiters were used to reduce numerical diffusion.

3.1 Effect of Different Suspension Limits

An 8 m^3 kick volume is considered. Here the suspension limit has been varied from 1 % to 7 %. When the gas volume percentage in a numerical cell is lower than the suspension limit, the gas will be trapped in the fluid. Also, the no suspension case has been considered indicated in the figures as 0 % suspension limit.

Figure 1 and Figure 2 show the pressure build-up at bottom and surface versus time when the kick migrates in the closed well. One can note that for increasing suspension limits, the final pressures achieved will be reduced significantly. One can also note that for the largest suspension limits (5 % and 7 %) the pressures stabilizes at a much earlier stage. One can also notice a change in the pressure build-up slopes around 2000 seconds for all cases.

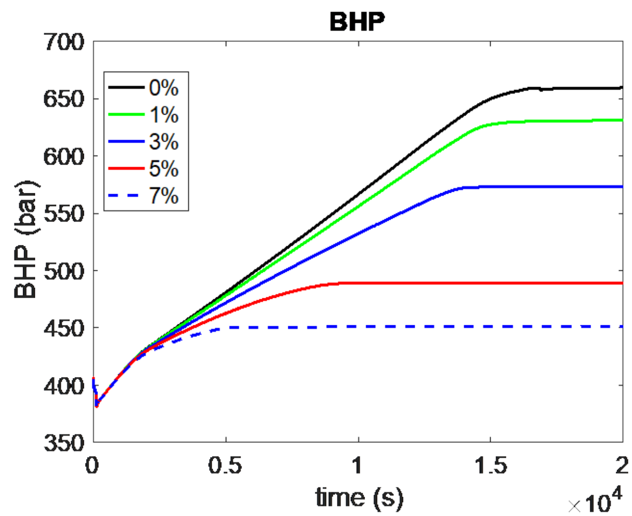

FIGURE 1: PRESSURE AT BOTTOM OF WELL VS. TIME [10]

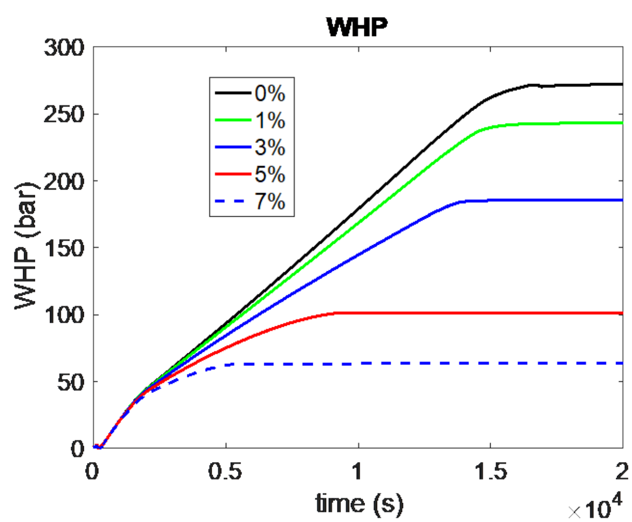

FIGURE 2: PRESSURE AT BOP VS. TIME [10]

Figure 3 shows the kick volume in the well vs. time for the various suspension limits. Here one can notice that the flow model can capture that the kick is allowed to expand slightly since the fluid volume is reduced because of the increasing pressure. Hence, we would get a different and less conservative result with respect to the magnitude of the final pressure compared to using e.g. Boyles law where it is assumed that the fluid is incompressible. We can notice that the kick is allowed to expand more for the cases with highest final pressure which correspond to the cases with no or low suspension effect.

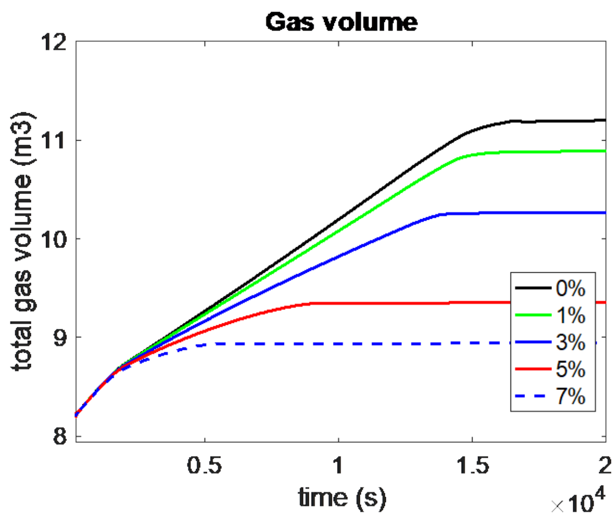

FIGURE 3: GAS KICK VOLUME VS. TIME [10]

For the sake of investigating further how the kicks are migrating, it is chosen to plot the gas volume fraction vs. depth at different time stages. Figure 4 shows how the gas is distributed in the well at time = 4000 seconds for the various suspension limits. We can notice that the bulk of the kick is migrating at the same speed for all the cases but the tail of trapped gas behind the kick varies. For larger suspension limits, more gas is getting trapped behind the kick and the volume of the bulk of the kick has been reduced. One can notice that the gas volume fraction is below 0.2 which indicates that the kick is migrating in the bubble flow regime at this stage. The gas velocities taken from the simulation also show gas migration velocities around 0.23 m/s which are typical for bubble flow (see Fig. 5). This figure also shows that for larger suspension limits, a smaller part of the kick is mobile at this stage.

The change in the pressure build-up slope seen earlier around 2000 seconds indicates the transition from slug flow to bubble flow. This will be discussed in a later example.

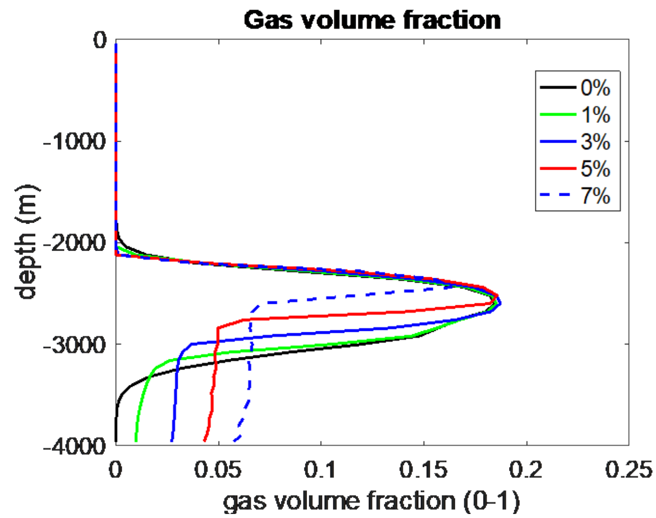

FIGURE 4: GAS VOLUME FRACTION AT 4000 SECONDS [10]

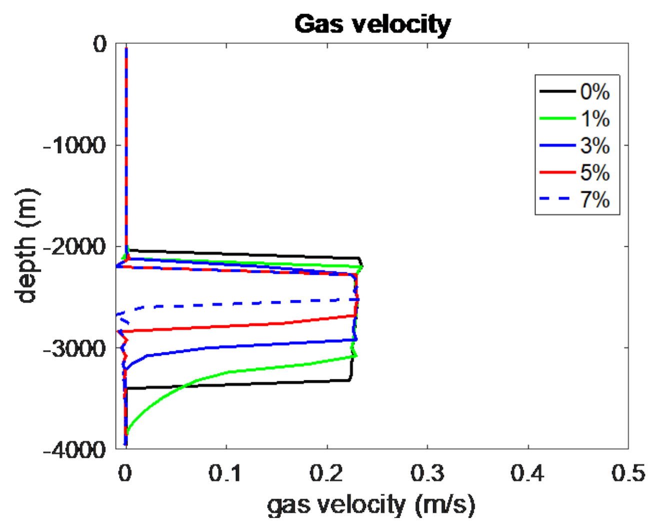

FIGURE 5: GAS VELOCITY AT 4000 SECONDS [10]

In Fig. 6, the gas volume fraction depth profiles at 10000 seconds is shown. Here one can notice that for the 5 % and 7 % suspension limits, the kicks have stopped migrating. They have become fully suspended in the fluid. This explains why the pressure stabilized at an earlier stage for these cases. One can also note that for the kicks that are still migrating, the bulk of the kicks are located approximately at the same position.

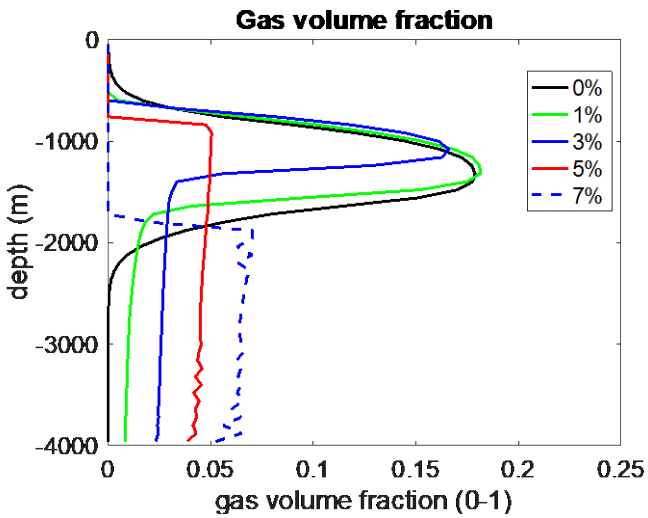

FIGURE 6: GAS VOLUME FRACTION AT 10000 SECONDS [10]

What one can see from this is that it is very difficult to say something about the real gas kick migration velocity based on measuring the rate of the pressure build-up at any stage. If one for instance, measure the pressure build-up at a very early stage, it seems similar for all cases. If one used this to estimate the gas migration velocity, one should note that for the 5 % and 7 % suspension limits, the kick will stop migrating at a later stage and become fully trapped by the fluid. There will also be a transition from slug flow to bubble flow taking place at around 2000 seconds which will change the slope of the pressure build-up. If one measures the pressure build-up at 10000 seconds, one can observe that the pressure build-up slope will be different for the 0 % (no suspension), 1 % and 3 % suspension cases where the kicks are still migrating. Hence, if one based the estimation of the migration velocity based on the pressure build-up at around 10000 seconds, one should obtain three different values. But as shown in Fig. 6, the bulk of the kick is in all cases at approximately the same position indicating a unique gas migration velocity for the case considered here.

The instant gas velocity can change throughout the simulation since there can be a transition from slug flow to bubble flow at a certain location. Hence the average gas migration velocity can vary. In addition, we have observed that the suspension effect can lead to fully trapped kicks which are characterized by an early pressure stabilization at a lower than expected pressure level.

In the following, a table is presented where the kick size and suspension limit have been varied. The average gas migration velocity has been estimated in different time intervals using the gas volume vs. depth plots. In cases, where the kick has become fully trapped, it will not be possible to estimate an average gas migration velocity which is indicated with the symbol (N/A). There might be some minor inaccuracies related to reading off the position of the kicks at different times properly.

TABLE 1: AVERAGE GAS MIGRATION VELOCITIES [10]

Kick Volume (m^3)	Suspension limits (%)	$S_{average}$ (m/s) (500-4000) sec	$S_{average}$(m/s) (4000-10000) sec.
4	0	0.21	0.24
4	1	0.21	0.24
4	3	0.23	N/A
4	5	0.27	N/A
4	7	N/A	N/A
8	0	0.32	0.21
8	1	0.32	0.21
8	3	0.32	0.25
8	5	0.32	N/A
8	7	0.32	N/A
12	0	0.57	0.19
12	1	0.57	0.19
12	3	0.57	0.19
12	5	0.57	0.23
12	7	0.57	N/A

From this table, one can observe that for the large kick of 12 m^3, the average gas migration velocity is 0.57 m/s in the time interval 500-4000 seconds. This is a typical value seen for slug flow. However, in the later time interval (4000-10000 seconds), the average gas migration velocity indicates bubble flow (around 0.2 m/s). For the 8 m^3, the average gas velocity in the early time interval indicates that both slug flow and bubble flow has been present in this time interval. The table also reveals that when the kick size is reduced, it is more likely that the kick will become fully trapped for larger suspension limits.

3.2 Effect of Changing Transition Interval between Slug Flow and Bubble Flow

In [5], it was observed that for gas concentrations larger than 10 %, the kick migration velocities seemed to be around 0.5 m/s when considering Non-Newtonian drilling fluids. Hence, the transition to slug flow seems to occur at a lower gas concentration compared to what is seen for Newtonian fluids like water. In the following, we will compare the effect of changing the transition interval from bubble to slug flow from 20-25 % to 10-15 % gas concentrations.

The same case scenario as in the previous example is used and the kick size is set to 8 m^3.

Figure 7 shows the pressure build-up at surface for the two different transition intervals for the no suspension case and 1 % and 3 % suspension limits. One can notice that the slope of the pressure build-up is reduced later in time (from 2000 seconds to around 3500 seconds) indicating that the transition from slug flow to bubble flow is delayed. However, the final pressure levels seem to be approximately the same for a fixed suspension.

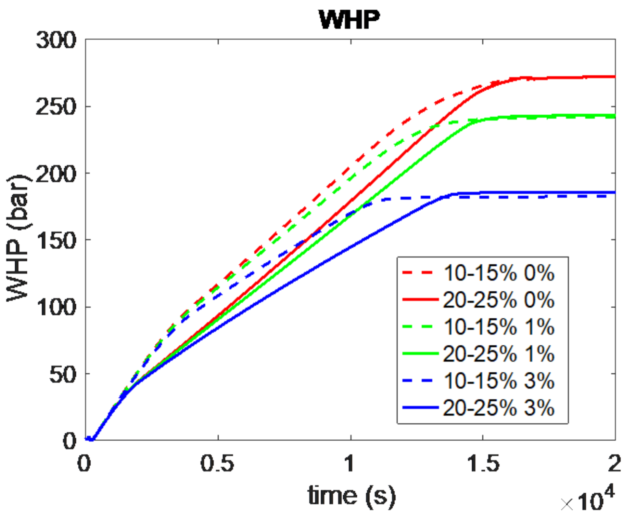

FIGURE 7: PRESSURE AT BOP VS. TIME [10]

For the sake of demonstrating the transition from slug flow to bubble flow, the gas velocity has been plotted at three different time instances (1000 seconds, 2000 seconds and 4000 seconds) for the two different transition intervals.

In Figure 8, the gas velocity vs. depth at 1000 seconds is shown. For both cases, slug flow is present with migration velocities around 0.5 m/s.

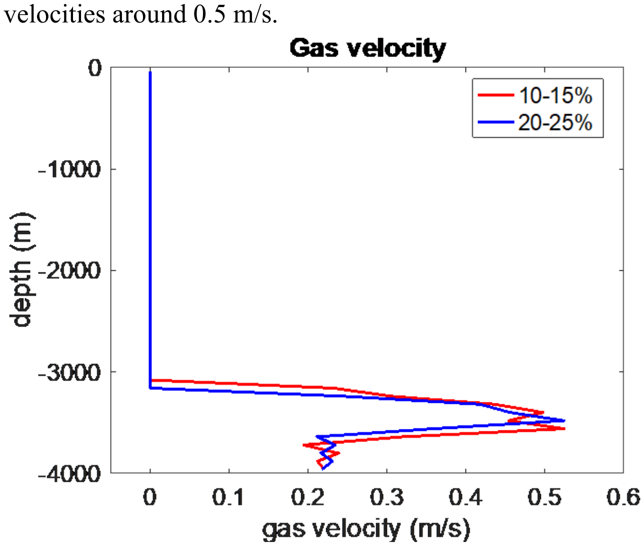

FIGURE 8: GAS VELOCITY AT 1000 SECONDS [10]

Figure 9 shows the gas velocity vs. depth at 2000 seconds. For the case where the transition interval is set to 20-25 % gas concentration, it is observed that the whole kick is migrating in the bubble flow regime with a migration velocity around 0.23 m/s. However, for the case with lower transition interval, the upper part of the kick is migrating with a velocity around 0.5 m/s which indicate slug flow while the lower part is in the bubble flow regime. In this case, the kick will migrate faster, and it will become more stretched out and the gas volume fraction will start to reduce.

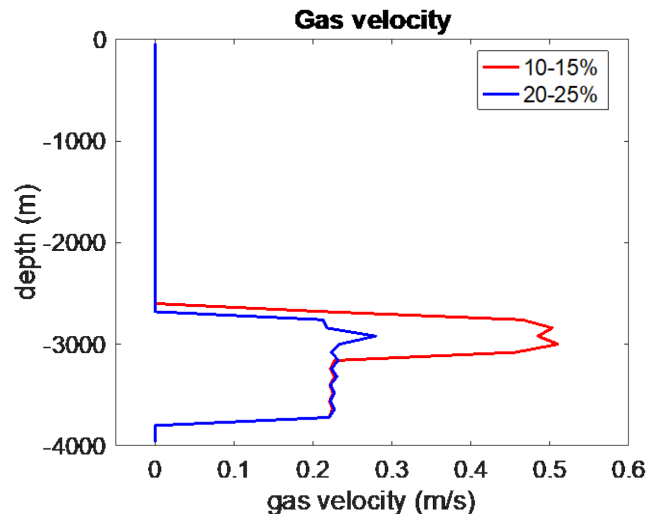

FIGURE 9: GAS VELOCITY AT 2000 SECONDS [10]

Figure 10 shows the gas velocity at 4000 seconds. For the case with lower transition interval, the kick has moved farther up in the well compared to the case with higher transition interval since part of the kick moved with migration velocities typical for slug flow. However, as mentioned before, the kick become more stretched out and the gas volume fraction is reduced such that at 4000 seconds, the whole kick is now close to migrating with a migration velocity typical for bubble flow. Hence, for the lower transition interval, the kick will stay longer in the slug flow regime but in the end, it will also migrate in the bubble flow regime. The main effect is that the kick will reach the BOP somewhat earlier compared to what will be seen considering the case with higher transition interval.

For the well geometry and the kick size considered here, it was interesting to note that the most dominating flow regime was bubble flow.

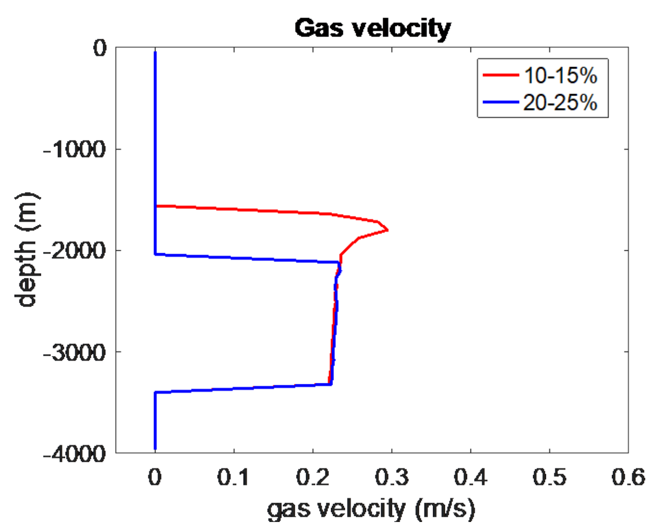

FIGURE 10: GAS VELOCITY AT 4000 SECONDS [10]

4. CONCLUSION

It has been demonstrated by use of a transient flow model incorporating different flow regimes that the gas suspension effect will have large impact on the pressure build-up when a kick migrates in a closed well. An increasing suspension effect will lead to a reduction in the slope of the pressure build-up and the final pressures achieved will become much lower. If the pressure stabilizes at an early stage with a low final pressure, it can be an indication that the kick has stopped migrating completely in the well.

The simulations also reveal that to use measurements of the pressure build-up in a certain time interval is not applicable to estimate gas migration velocities. One reason is that the kick migration velocity can change vs. time since it can start migrating in the slug flow regime but then end up in the bubble flow regime. It can also stop migrating completely even though an initial pressure build-up was observed.

Another reason is that as long as a kick migrates in a single flow regime e.g. bubble flow, the bulk of the kick will migrate at the same velocity even if the suspension effect is varied. But it has been shown that by varying the suspension limit, the slopes of the pressure build up varies and it is therefore impossible to deduce a unique gas migration velocity from these slopes. But the bulk of the kick migrates with a unique velocity independent of the chosen suspension limit according to the simulations. The results obtained confirm what was discussed in [1]

The simulated response of shifting the transition interval from bubble to slug flow such that the slug flow will take place for lower gas volume fraction was also demonstrated. The main effect is that the kick will stay in the slug flow regime for a longer period but in the end, the kick will migrate in the bubble flow regime for both the transition intervals considered. Hence the kick will reach the surface slightly earlier for the low transition interval. But the final pressures achieved were the same.

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