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NUMERICAL MODELLING AND SENSITIVITY ANALYSIS OF GAS KICK MIGRATION AND UNLOADING OF RISER

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ABSTRACT

In deepwater wells there is a risk of gas entering the riser. This can be caused by gas being trapped by the BOP after a well kill operation, or it can be that the BOP was not closed quickly enough upon kick detection. With oil-based mud (OBM), gas is dissolved, and larger kicks may go undetected and circulated up in the riser by accident.

If a gas kick comes into the riser, a rapid unloading event can occur. This can in worst case lead to a blowout scenario. In addition, the riser may be subject to a collapse load due to reduced liquid level inside. The unloading behavior will be different when comparing kicks in oil-based and water-based mud (WBM).

For water-based muds, field experience and experiments have shown that gas can be trapped by the mud. This effect is the same that causes mud to capture cutting particles, and it is related to the non-Newtonian and time-dependent rheology behavior of the mud. The suspended gas can only be removed from the riser by circulation. The kick must therefore be of a certain volume to be able to unload the well.

Modelling of the mentioned complex phenomena, with the violent transient phase seen when a large volume of gas expands as it moves towards the liquid surface in the riser, is still a challenge for numerical algorithms to do accurately and reliably. Robust handling of numerical diffusion in two-phase flow is one of the key topics, as are slippage and extension of gas in the liquid.

The paper describes how an explicit numerical scheme (AUSMV) is used as a numerical solver with the application of the slope-limiter technique to handle numerical diffusion. This has not yet been done for unloading of gas in riser.

A simulation case will be constructed considering gas migration and expansion in a long riser. A sensitivity analysis will be performed where both the kick volumes and the threshold for gas suspension will be varied to study when kicks will start to unload the well vs. situations where they will become fully suspended. The phenomena mentioned will be studied for water-base drilling fluids.

The paper will review previous work on the subject and highlight how transient flow models can be useful for gaining more insight into how the gas behaves in risers and what can be done to mitigate the consequences.

Key words: riser unloading, drift-flux model

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INTRODUCTION

In deep water drilling, there can be a risk for having a gas kick in the riser. This can be due to improper kick detection such that the BOP was not closed early enough. However, trapped gas in a closed BOP can also be released to the riser at a later stage when the BOP is opened after a well kill. When the kick migrates or is circulated towards the surface, a rapid unloading event will occur that in the worst case can lead to explosions, a collapse of the riser and a blowout scenario.

A kick will behave differently in oil-based vs. water-based mud. In oil-based mud, it will remain fully dissolved until the bubble point is reached but then it may unload very rapidly due to the cascading effect discussed below, even though bubble point depends on the gas fraction, which causes degassing to be a gradual process. There is a more significant risk for surprise since a kick in OBM can easily be undetected until the bubble point is reached. In general, a dissolved gas kick has to be circulated out to reach the surface.

A kick in water-based mud will usually migrate on its own without additional circulation. However, this is only partly true. Field tests have shown that the kicks tend to be dispersed instead of migrating as large slugs [1, 2]. For smaller kick volumes, the gas can become entirely trapped in the mud and can only reach the surface by circulation. However, the latter represents an operational risk if the crew is not aware of having a kick in the riser when starting to circulate it or are using too large circulation rates. According to [3], this was believed to be the cause behind the Zapata Lexington accident (September 1984). When it comes to unloading, also a kick in WBM will evolve rapidly when approaching surface. The gas will roughly double its volume for each halving of the hydrostatic pressure. When the kick is near the surface, the expansion of the gas will increase dramatically and may expel large amounts of mud in the riser. This will eventually lead to a reduced mud level in the riser and potentially a riser collapse situation. If the BOP is not closed during the riser circulation, a reduction in bottomhole pressure will also be seen that may lead to a secondary kick inflow.

Experiments and Field Observations

In [4], gas migration velocities were discussed in view of small scale lab experiments and experience from the field tests. They highlighted that for Non-Newtonian fluids, gas would be suspended and trapped by the mud for smaller gas volumes. The bulk of the kick will migrate fast but will leave a trail of bubbles that will be trapped. For a closed well, this will lead to a different pressure build-up that can lead to a misinterpretation that the kick is migrating slowly.

Field tests conducted by three major operators in 1986 were reported in [1]. The riser had a 17 ½ inch ID and was 3118 feet long. Air kicks with volumes ranging from 10 to 50 bbls were injected at the bottom of the riser. The tests showed that the gas became dispersed and did not migrate as a slug. The kick volumes considered also got trapped in the riser when no circulation took place.

A field test in deepwater (2741 meter water depth) was presented in [2]. The riser ID was 19.5 inch. A small gas kick was introduced and circulated out of the riser. Also here it was observed that the gas kick was spread out. The experimental data was compared with a fully transient simulation model, and a reasonable match was seen. It was highlighted that the modelling of gas migration in a non-Newtonian fluid with yield stress is complex. However, it was clear that the flow model gave much better results compared to what a single bubble approximation assuming gas occupying the whole cross-sectional area would have given.

Field tests for a controlled mud level drilling system were presented in [5], where the mud level in the riser is reduced to overcome specific drilling challenges and introduce a dual gradient effect. They carried out 5 tests, and in the final test, a gas kick was introduced in the riser. This unloaded the riser and reduced the final mud level to a lower value. It was commented that some of the gas was probably strung out in the annulus after the unloading event.

An experiment using a setup that simulated a controlled mud level drilling system was reported in [6]. The setup had a 27 feet riser model, an inlet pump to circulate liquid through the system and an outlet pump to control mud level and discharge rate from the riser. An injection port located at the base of the model was used to inject gas into the system. It was observed that as the discharge rate was increased the amount of gas that could be diverted increased only to a certain extent. When the inlet pump rate was increased the bubbles became smaller and more dispersed. This resulted in a greater amount of gas being diverted from the riser.

An update of this study was presented in [7]. A vacuum pump was added to the setup to run experiments in vacuum to observe gas expansion in the riser. This was not observable in their previous study due to a limitation in riser height. The experiments were conducted under vacuum condition with no circulation. At atmospheric and under 10 psi vacuum pressure they observed no gas expansion. When the pressure was reduced to 5 psi the gas volume of the gas bubbles had doubled in size as they migrated to the top of the flow loop. When the pressure was reduced to 1.95 psi the gas expanded more than 10 times.

Models for Gas in Riser

In the following, an overview of some of the models developed for studying gas kicks in riser has been presented.

Simulations of a kick being circulated in a riser using an advanced kick simulator is shown in [3]. A model was included for gas being suspended in mud, but no details about the model were shown. They also included bubble and slug flow. In the simulations, a gas volume fraction of 1 % was trapped in the mud. They showed small kicks could become entirely trapped when migrating in a stagnant liquid and in these cases, they will have to be circulated out. One of the operational recommendations was to let the gas migrate in riser first and then circulate it out instead of starting circulating immediately. This allows the gas to become more spread out and leads to lower maximum gas rates at the surface. This recommendation was also given at an earlier stage by e.g. [8].

A model for dynamic simulation of gas migration in marine riser was presented in [9]. The kick was modelled as a bubble occupying the whole cross-sectional area and separated from the mud below and above. They introduce the riser equilibrium point where the pressure of the gas bubble no longer will be balanced by the hydrostatic pressure of the mud above. When this is reached, an explosive unloading of the riser will occur. Their model was based on tracking an expanding gas bubble migrating upwards in the riser and calculate lengths of mud and gas zones. When the lengths no longer could fit within the riser, the riser equilibrium point has been reached. They considered both oil and water-based mud. The model was based on assuming an incompressible mud, no riser friction and the end velocity of the gas bubble was approximated using either the mud velocity defined by the boost pump or Taylor bubble velocity (gas rise velocity).

More details about the abovementioned method can be found in [10]. Here, the model was extended to include effects related to riser friction, acceleration terms, and riser backpressure. He also considered the drift-flux model and performed simulations for a simplified case.

A mathematical model for migration of a single gas bubble in a riser considering water-based mud was also presented in [11]. This model considers the gas bubble to occupy the whole cross-sectional area of the riser. The model was adapted for various outlet boundary conditions (conventional drilling, back pressure MPD and controlled mud level in the riser (CML)). Acceleration and friction effects were included, and a single slip relation was used. The slip relation was tuned to obtain a match between simulated data and field observations.

A simulation study was reported in [12], where a transient flow model (OLGA 2016) was used to study the gas unloading in risers. The controlled mud level system (CML) where the mud level in the riser is reduced was the primary focus, and comparison with field data [5] for this system was initially shown. The paper showed simulations of gas in riser for both oil-based and water-based muds. Effect of reducing circulation rates and using a backpressure on top of the riser on maximum gas and liquid rates at the surface was shown. The use of backpressure to make it possible to handle riser gas was highlighted. The maximum outlet rates were worst for the oil-based mud scenario. The bubble point vs. influx volume was also shown. The paper also made some analysis of water hammer effects if the riser is closed rapidly on top.

DRIFT-FLUX MODEL

The drift-flux model will be used for describing kick migration and unloading of riser. A fixed temperature gradient will be assumed. Only water-based drilling fluid will be considered. Hence no mass transfer will take place between the phases.

Conservation of mass of drilling mud:

$$\frac{\partial}{\partial t}(A\alpha_l\rho_l)+\frac{\partial}{\partial z}(A\alpha_l\rho_l v_l)=0 \tag{1}$$

Conservation of mass of gas:

$$\frac{\partial}{\partial t}\left(A\alpha_g\rho_g\right)+\frac{\partial}{\partial z}\left(A\alpha_g\rho_g v_g\right)=0 \tag{2}$$

Conservation of mixture momentum:

$$\frac{\partial}{\partial t}A\left(\alpha_l\rho_l v_l+\alpha_g\rho_g v_g\right)+\frac{\partial}{\partial z}A\left(\alpha_l\rho_l v_l^2+\alpha_g\rho_g v_g^2+p\right)= -AF_{fric}-A\rho_{mix}g\cos\theta \tag{3}$$

$$\alpha_g+\alpha_l=1 \tag{4}$$

Here subscript g and l represents gas and liquid (mud) respectively, A is the cross-section area, z is the spatial dimension, t is time, α_g volume fraction gas, α_l volume fraction liquid, g is the gravity acceleration, θ is the angle of inclination, F_{fric} is the frictional pressure loss, ρ_l the density of mud, ρ_g the density of gas. The mixture density is defined by $\rho_{mix}=\rho_l\alpha_l+\rho_g\alpha_g$.

Additional closure laws have to be provided to close the system. The mud density is given by:

$$\rho_l=c\rho_{wt}+(1-c)\rho_w \tag{5}$$

where ρ_{wt} is the density of the incompressible weight material and c is the volume fraction [0-1] of weight material in the drilling fluid. The water density is given by:

$$\rho_w=\rho_0+\frac{\rho_0}{\beta}(p-p_0)-\rho_0\alpha(T-T_0) \tag{6}$$

The different parameters are given in the following table.

TABLE 1: WATER DENSITY MODEL PARAMETERS

$\rho_0\ (\frac{kg}{m^3})$	$p_0\ (Pa)$	$T_0\ (K)$	$\beta\ (Pa)$	$\alpha\ (K^{-1})$
1000	100000	293	$2.2\text{x}10^9$	0.000207

For the gas density, air is assumed mimicking a controlled experiment of gas migration in a riser. Ideal gas law is assumed.

$$\rho_g=\frac{p}{RT} \tag{7}$$

Here $R=286.9\,J/(kgK)$ and T is the temperature in Kelvin.

The frictional pressure loss model is given by:

$$F_{fric}=\frac{2f\rho_{mix}v_{mix}|v_{mix}|}{(d_{out}-d_{in})} \tag{8}$$

Here f is the friction factor, mixture velocity $v_{mix}=v_l\alpha_l+v_g\alpha_g$ and d_{out} and d_{in} refers to inner diameter of riser and outer diameter of drillpipe. The friction model is presented in more detail in [13]. Since the riser has a huge diameter, frictional pressure losses are expected to be low.

Since a mixture momentum equation is used, the missing information must be supplied by using a gas slip relation.

$$v_g=Kv_{mix}+S \tag{9}$$

where K and S are flow regime dependent parameters. This model will be discussed in more detail in the next section.

GAS SLIP MODEL

In water-based mud, a gas kick will migrate on its own to surface both in closed and open wells. Knowledge about the gas migration velocity is vital for predicting when the gas kick can be expected at surface. For a deep water well where the kick has been taken at a shallow depth below the seabed, it will be important to know how early one has to close the BOP to avoid that a kick enters the riser, and how things may evolve if closing too late. When the kick has entered the riser, the secondary barrier element has failed, and one can only rely on the diverter to minimize the impact.

Gas migration velocity will also determine how fast pressures in the well build up during a shut-in situation. At a certain point, circulation of kill fluid has to be initiated before the increasing well pressures cause fracturing of the formation.

For oil-based mud, the kick may be fully dissolved, and the situation is different. Here, the whole kick usually has to be circulated out of the well. Besides, more massive kicks may go undetected and circulated up in the riser by accident.

Gas slip may also have a mitigating effect in that the gas front typically moves faster its tail, and by that gas may spread out over a considerable depth range. All in all, the complexity of the process suggests that an advanced dedicated two-phase model is required for good predictions and understanding.

Free gas migration is usually modelled using the gas slip relation [14]:

$$v_g = Kv_{mix} + S = K(v_l\alpha_l + v_g\alpha_g) + S \qquad (10)$$

Here, K is a parameter related to how the gas is distributed across the annulus while the gas slip velocity S represents the gas velocity relative to the liquid with zero velocity. For no slip conditions, $K = 1.0$ and $S = 0$.

In two-phase concurrent upward flow, different flow patterns like bubble, slug, dispersed bubble, churn and annular flow can occur, see e.g. [15] and their study of Newtonian fluids. Other flow configurations like countercurrent and downward flow can also take place [16]. The values or models for K and S will vary depending on flow configuration and which flow pattern that is present.

Bubble Flow

This will typically take place for gas volume fractions below 0.25, see e.g. [15]. For larger gas volume fraction, Taylor bubbles will form and slug flow will appear. This transition limit has also often been adopted for kick models where non-Newtonian fluids are present [17]. Typically, a gas kick will migrate faster in slug flow compared to bubble flow. For non-Newtonian fluids, there is experimental work showing that the transition between bubble and slug flow may take place at a lower gas volume fraction [4], with reference to the work carried out in [18]. For gas fractions above 0.1, the gas migration velocities were larger for non-Newtonian fluids compared to what was seen for Newtonian fluids. This was explained by the fact that the viscosity of the drilling fluid would hinder the bubble break up process allowing the gas to travel as bigger bubbles. The S value reported was around 0.5 m/s, which is close to what typically will be seen for slug flow.

The K value for bubble flow considering Newtonian fluids often varies between 1.0 [19], 1.1 [15], and 1.2 [16]. In [17] $K = 1.0$ in the kick model presented.

The gas rise velocity S for bubble flow is often modelled using the equation proposed by [20]:

$$S = 1.53\left(\frac{(\rho_l - \rho_g)g\sigma}{\rho_l^2}\right)^{0.25} \qquad (11)$$

It is seen that the expression depends on the difference in fluid densities, gravity acceleration and interfacial tension σ. In [15], it is reported that some authors modify this expression by using $S = S(1 - \alpha_g)^n$ where $0.5 \leq n \leq 2$. This is to take into the effect of having a swarm of bubbles.

In general, when considering kick modelling in non-Newtonian fluids, the values and models for $K$and S are typically based on what has been used for Newtonian fluids.

In the work presented here $K = 1.0$ and S given by Eq. 11 will be adopted for bubble flow. We have chosen to define the transition to slug flow for a gas volume fraction between 0.2 and 0.25 using linear interpolation techniques. However, this transition can be lowered in future studies to mimic that the transition to slug flow may take place for lower gas volume fractions when considering non-Newtonian fluids.

Slug Flow

This flow pattern is characterized by the migration of Taylor bubbles followed by liquid slugs. Here K takes the value of 1.2 [15] [16] and this is also typically used for non-Newtonian fluids [17].

The gas rise velocity when considering a vertical pipe configuration is given by the following expression [16] [18]:

$$S = 0.35\sqrt{\frac{g(\rho_l - \rho_g)d}{\rho_l}} \qquad (12)$$

Here, d is the pipe diameter. This expression has to be modified to take into account the effect on having inclination with the vertical and annular geometry. The following corrections with reference to previous work were given in [16].

$$S = S\left(1 + \frac{0.29d_{in}}{d_{out}}\right)\sqrt{cos\theta}(1 + sin\theta)^{1.2} \qquad (13)$$

Here θ is the deviation angle from the vertical. However, one can note that the expressions found for S in the literature vary. Some examples of different formulations can for instance be found in [3], [15], and [19]. Also for slug flow, it seems common to transfer the models developed for Newtonian fluids to non-Newtonian fluids. In the work here, $K = 1.2$ and S given by Eq. 13 will be adopted for slug flow.

As mentioned before, other flow patterns like churn flow and annular flow may occur during two-phase flow. During an unloading scenario of riser, it might be that these flow patterns will be encountered. However, modelling of this has to our knowledge not been reported in literature when considering models for kick simulation. Hence, the slug flow model will be used for gas volume fractions up to 0.6. If the gas slip relation is rewritten, it will take the following form:

$$v_g = \frac{(K\alpha_l v_l + S)}{(1 - K\alpha_g)} \qquad (14)$$

To avoid division by zero, the K value is reduced linearly from 1.2 to 1.0 for gas volume fractions between 0.6 and 0.8. The S value is reduced linearly to 0 for gas volume fractions in the range 0.6 to 1.0. So effectively, we introduce no-slip conditions when approaching one-phase gas flow. It can be mentioned that the stability of the numerical simulations can be quite sensitive to the width of the interpolation interval for S. when it was made too narrow, numerical challenges were observed. The problems were also more pronounced when using a rough discretization instead of a more refined discretization.

Suspension

As discussed in the literature review, both small scale experiments [4] and field tests [1, 2] have shown that gas can become trapped in non-Newtonian fluids. This will correspond to having no slip conditions where $K = 1$ and $S = 0$ in the gas slip model. This will take place for small gas volume fractions. When a kick enters a riser, it will become suspended due to this effect. In some cases, the kick will have to be circulated out [1]. Whether the kick will become fully suspended or be able to migrate to surface on its own will depend on the initial kick size, riser area, and riser length. In addition, it will depend on at which gas fraction the suspension will take place. In [4], it was shown experimentally that the suspended gas fraction could vary from 0.005 to 0.05 when the yield stress of the mud varied from 10 to 50 lb/100 ft^2. Simulations using an advanced kick simulator were presented in [3] where it was developed a model for which gas fraction suspension took place. No details about the model were presented, but it depended on yield stress of the mud which again depends on pressure and temperature conditions.

$$\alpha_{g,susp} = f(yieldpoint, pressure, temperature) \quad (15)$$

As pointed out in [4], the yield stress of the mud will change depending on the operational conditions. When the well becomes static, yield stress will increase depending on time, which again impact how much gas can be trapped.

In the simulations presented here, the impact of using different fixed values for $\alpha_{g,susp}$ will be demonstrated. The gas volume fraction transition interval from having full suspension $\alpha_{g,susp}$ to fully developed bubble flow was set to 0.04.

NUMERICAL SCHEME

The full drift-flux model represented by Eqs. 1-9 includes the acceleration terms that are associated with generation of sonic waves. The model describes both waves related to mass transport and sonic waves, and it is classified as a system of hyperbolic nonlinear partial differential equations which will require an accurate numerical method for capturing sharp discontinuities. Especially, the numerical method has to capture the sharp interface that will occur between a liquid flow region and a two-phase flow region. This will be especially important when studying gas unloading in a riser where the expanding gas will force the liquid in front out of the well.

One can also note that when using the full drift-flux model for studying unloading, effects of friction and acceleration terms are naturally included. Besides, one can easily incorporate the effect of gas suspension and gas slippage for various flow patterns.

The explicit AUSMV scheme will be used here as the numerical solver. More details on the scheme can be found in [21], [22], and [23]. The description below follows what was presented in [13].

The riser is discretized into N cells from bottom to top.

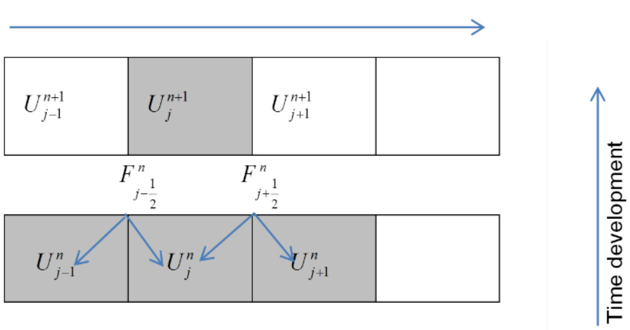

FIGURE 1: UPDATE OF DISCRETIZED VARIABLES [13]

The three conservation laws Eqs. 1-3 are updated using the following expression:

$$U_j^{n+1} = U_j^n - \frac{\Delta t}{\Delta z}\left(F^n_{j+\frac{1}{2}} - F^n_{j-\frac{1}{2}}\right) + \Delta t Q_j^n \quad (16)$$

Here U is a vector representing the conservative variables$\left(A\alpha_l\rho_l, A\alpha_g\rho_g, A\left(\alpha_l\rho_l v_l + \alpha_g\rho_g v_g\right)\right)$. These variables are considered constant for each cell representing the mid value of the cell. The numerical flux vector $F^n_{j+\frac{1}{2}}$ is calculated based on left- and right-hand side values defined by $\left(U_j^n, U_{j+1}^n\right)$ using formulas that are specific for the AUSMV scheme. It can be noted that the fluxes are calculated using old time level values indicated by superscript *n* making the scheme explicit in time. *Q* is a vector representing source terms. Since we only will consider gas migrating in water-based mud, no mass transfer between phases will take place and it will have the form: $(0{,}0, -AF_{fric} - A\rho_{mix} g cos\theta)$.

When a new time update *(n+1)* of the three conservative variables has been performed for all cells, one needs to combine these with the additional closure laws to find the physical variables represented by pressure, phase densities, phase volume fractions, and phase velocities. The time step is limited by the CFL criterion $\Delta t \leq CFL \frac{\Delta z}{speed\ of\ sound}$ where the *CFL* number is lower than 1. Here, a CFL number of 0.25 is used.

Numerical Boundary Treatment

The numerical fluxes at the bottom and top of the riser must be found by other means than using the AUSMV formulas.

At the bottom of the riser, mass fluxes of liquid and gas will be given. The gas rate will be used to define the entrance of the kick and after that it is set to zero. The liquid mass rate will be zero if no circulation takes place or it will have a value defined by the circulation rate through the boost line. I.e. any dynamics due to additional gas below the riser or temperature effects in the well are ignored as the focus in on riser dynamics. The mass rate on top of the boost line will be the same as on the bottom.

However, the pressure has to be estimated using the following formula:

$$p_{bottom} = p_1 + \frac{\Delta z}{2}\rho_{mix,1} g cos\theta_1 + \frac{\Delta z}{2} F_{fric,1} \quad (17)$$

Here one can note that the number 2 relates to the fact that variables are defined in the midpoint of a cell.

At the outlet of the riser, atmospheric pressure is assumed. The fluxes related to mass and momentum at the outlet are found by using second-order extrapolation techniques of the values for phase densities, phase velocities and phase volume fractions. The use of second order techniques instead of first-order techniques seemed to give more stable numerical results for the gas unloading scenario.

Increased Numerical Accuracy

When a gas kick unloads a riser, it is important to reduce the effect of numerical diffusion to resolve the sharp interfaces that will occur between the one-phase and two-phase regions. This will be important to get more accurate predictions of the magnitude of the maximum rates that will occur as well as a sharp resolution of the reduced mud level in the riser after the unloading.

There are two ways of improving the accuracy. One approach is to increase the number of cells. The other is to introduce the slope limiter concept to extend the AUSMV scheme to second order. In this case, the flow variables in a cell are no longer considered constant but piecewise linear. In this work, the minmod limiter has been used [24]. The use of slope limiters was also for instance used by [13], [25], and [26]. Hence, before calculating numerical fluxes, the values of pressure, phase densities and phase volume fractions on each side of a cell boundary are found using piecewise linear reconstructions for each variable. For details on how one performs these calculations for one variable, one can consider [27]. It can be noted that we omitted using slope limiters on the phase velocities since it tended to give less stable numerical behavior. For the numerical cells at the bottom and top of the riser, the slope limiters were copied from the nearest interior cell.

Increasing number of boxes will give more accurate results whether we use slope limiters or not. When using slope limiters, the scheme will reduce numerical diffusion and converge faster to the anticipated true solutions when refining the grid. This requires less computation time. One can start with a given grid size and then double the number of cells until the results (e.g., maximum rates) do not change much anymore. Then a sufficient number of cells has been reached to produce results where the effect of numerical diffusion has been reduced to an acceptable level.

SIMULATIONS & DISCUSSION

After setting up the AUSMV scheme in MATLAB to simulate a gas-in-riser event, 4 cases were defined to study the transient behavior of critical parameters. Among the objectives are to study a possible riser unloading situation, its impacts, and in which conditions it is more likely to occur. We also show the impact of adopting different suspension limits. In Case 1, the effect of numerical diffusion is demonstrated. In Case 2, we provide a comparison between different suspension limits and show the consequences. In Case 3, different kick sizes are introduced in the well and migrate without the aid of the mud pump. The impact of kick size is demonstrated. In Case 4 a suspended kick is circulated at different pump rates, and the results are discussed. The input parameters were inspired based on field and experimental data published by the authors cited in the previous sections and other references. Some input parameters of interest are provided in Table 2.

TABLE 2: SUMMARY OF THE DATA ADOPTED FOR THE SIMULATIONS

Parameter	**Description**
Riser depth	3000 m (9843 ft)
Riser diameter	0.4826 m (19 in)
Drillstring diameter	0.127 m (5 in)
Type of mud	Water (1.0 sg)
T at the bottom of the riser	65°C (assumed)
Temperature at surface	25°C (assumed)
Pressure at the top of the riser	100000 Pa (1bar)
CFL (defined in text)	0.25

Case 1 – Varying Grid Refinement

In Case 1, the grid refinement is varied. Simulations of a 6 m^3 kick being circulated at 40 kg/s (2400 lpm) were performed using 25, 50, 100, 200, and 400 boxes. To have a consistent CFL number for all simulations, the time step was halved when doubling the number of cells. The suspension limit adopted was 3%. The results are provided in Figs 2-5. Increasing the number of boxes will reduce the numerical diffusion, and since we use slope limiters, one will converge faster towards the anticipated exact numerical solution. When the grid was refined from 100 to 200 boxes, the results in Fig 2-5 do not change significantly. In Fig 3, we have included a simulation with 400 boxes, and it is observed that the maximum pit gain does not change considerably from the one obtained by using 200 boxes. If we increased the number of boxes further, the computational time would increase, but the accuracy would not increase enough to justify a more refined grid. Thus, a discretization of 200 boxes was adopted for Cases 2, 3, and 4 to be presented later.

For the conditions simulated in Case 1, the riser is unloaded, but mud is circulated to refill the well. The gas is circulated and expands on its way up causing a drop in the hydrostatic column effectiveness. As seen in Fig. 2, the pressure at the bottom of the riser tends to decrease as the gas goes up, reaching its minimum value when gas reaches the surface. The pressure starts to increase again when the kick leaves the riser. As the mud is replaced, the pressure is reestablished. The expanding gas pushes the same volume of mud above it, causing an increase in the pit gain, as shown in Fig. 3. The effect of the mud arriving at surface is also contemplated in Fig. 4, where the maximum liquid rate occurs at the same moment as the maximum pit gain is observed. Fig. 5 shows that the gas arrives at surface right after the maximum liquid rate is observed.

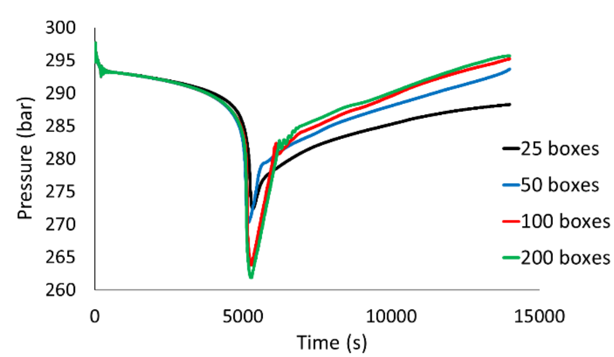

FIGURE 2: PRESSURE AT THE BOP VS. TIME (CASE 1)

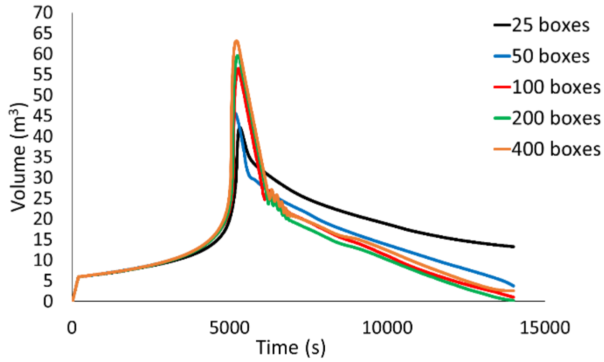

FIGURE 3: PIT GAIN VS. TIME (CASE 1)

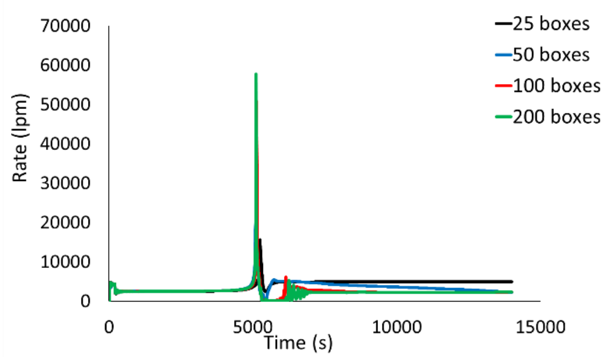

FIGURE 4: LIQUID RATE AT SURFACE VS. TIME (CASE 1)

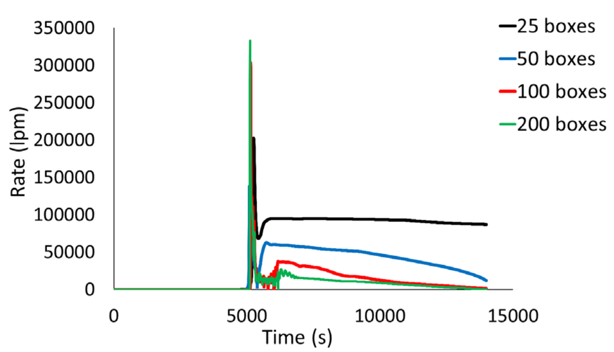

FIGURE 5: GAS RATE AT SURFACE VS. TIME (CASE 1)

In practice, increasing the number of boxes restricts numerical diffusion. Higher maximum rates will be predicted when numerical diffusion is reduced and the drop in bottomhole pressure will be more pronouced. The accuracy in these predictions is crucial, as underestimating the key parameters might compromise the system limitations (for instance overcome the separator's capacity) or mislead the crew's actions on the rig.

Case 2 – Comparing Suspension Limits

In Case 2, the effect of the suspension limit is studied. Here, the pumps are off, and the gas migrates on its own, relying mainly (but not only) on its density discrepancy with relation to the mud. The input parameters presented in Table 2 are also valid here. An 8 m^3 kick is injected in the bottom of the riser considering the following suspension limits: 0, 1, 1.5, 2, 2.5, and 3 percent. Figs 6-12 show the simulation results. The gas becomes fully suspended for gas volume fractions below the suspension limit. So if the suspension limit is zero, the gas will fully migrate, in this case, leading to a riser unloading situation. The *no suspension* case is the case in which the gas and liquid rates are the highest (Figs. 8-9), and which gives the lowest pressure at the BOP after the unloading (Fig. 6). The pressure drop reflects how much the mud level has been reduced in the riser after the unloading. We also observe that the friction in the riser is largest for this case (Fig. 11). It is normal to assume that friction in wide risers is negligible but it is seen here that when the maximum rates are achieved, some friction can be expected and should be considered in the modelling process.

For the case where we consider that 1% of the gas gets trapped in the mud, a smaller amount of gas (compared to the *no suspension* condition) will migrate, and thus smaller gas and liquid rates are observed at the surface. The riser unloading phenomenon becomes less dramatic. When considering the 3% suspension limit, the kick becomes fully trapped. The limit for when the kick becomes fully suspended is between 2.5 and 3%, according to the simulations. There will be no gas flow at the surface, and the liquid rate at the surface is also negligible and zero in the end when the kick has stopped migrating. The pressure at the BOP is also nearly constant. The pit gain shown in Fig. 7 reflects the gas volume in the well, and it only increases slightly from its initial value of 8 m^3 in the 3% suspension case. This increase is because the gas is allowed to expand slightly on its way upwards before it becomes trapped. Fig. 10 shows that for the 3% suspension limit, the total mass of liquid in the well is almost constant meaning that almost no liquid was forced out of the well. In contrast, for the 1% suspension limit and *no suspension* case (0 %), the mass of liquid in the well at the end of the simulation (after the unloading) is much less than when the kick entered the riser. It is lowest for the no suspension case indicating that the final mud level in the riser will be lowest for this case.

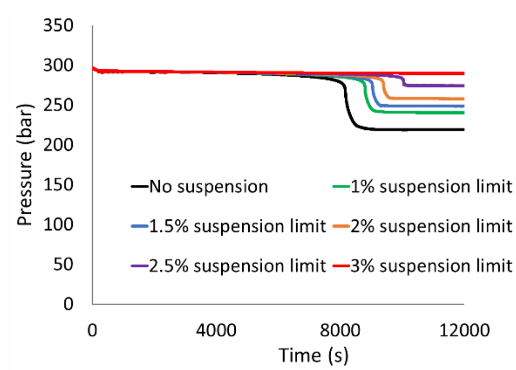

FIGURE 6: PRESSURE AT THE BOP VS. TIME (CASE 2)

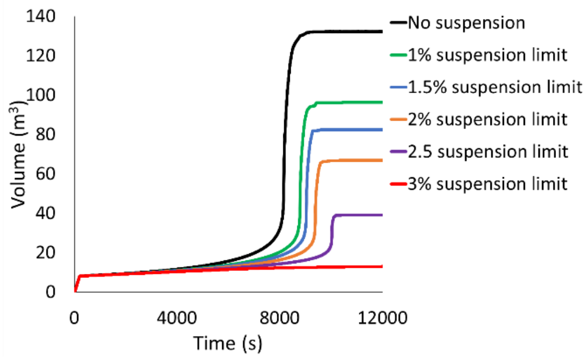

FIGURE 7: PIT GAIN VS. TIME (CASE 2)

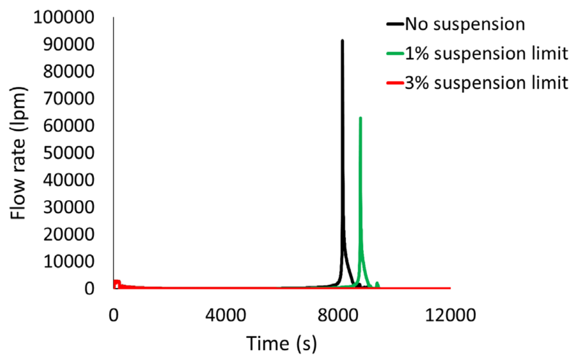

FIGURE 8: LIQUID RATE AT SURFACE VS.TIME (CASE 2)

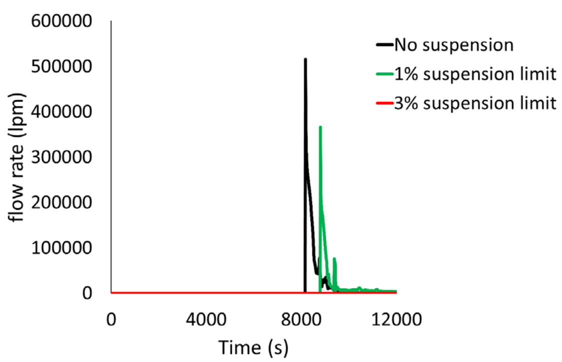

FIGURE 9: GAS RATE AT SURFACE VS. TIME (CASE 2)

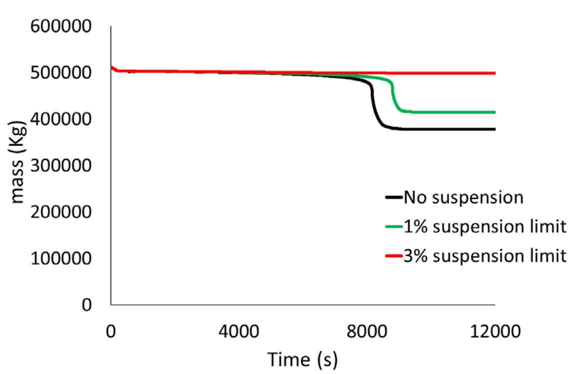

FIGURE 10: LIQUID MASS IN THE RISER VS. TIME (CASE 2)

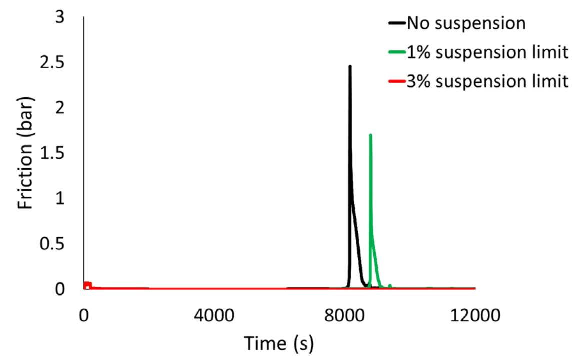

FIGURE 11: FRICTION IN THE RISER VS. TIME (CASE 2)

The riser unloading occurs at around 8000 seconds, as shown by the time profiles obtained for this case. Fig. 12 shows the gas fraction in the well at 7000 seconds, which is before the gas arrival at the surface. This plot shows that, at 7000 seconds, most of the migrating gas is located between 700 and 1500 m below the surface. Below 1500 m, it is possible to observe a tail of suspended gas, corresponding, in each case, to the suspension limit considered. In the *no suspension* case, no gas gets trapped in the mud, while for 3% suspension limit almost all the gas has become suspended at this moment and there is only a small part of the kick still migrating upwards. Fig. 13 shows the gas fraction along the riser after 15000 seconds elapsed time and it shows how the gas gets trapped at 3% volume and stops at around 460 m below the surface. Note that for any suspension limit above 3%, an 8 m^3 kick will be fully suspended and will not reach the surface, when considering the input parameters used here. One can also observe that when including gas suspension, it will have an impact on when the unloading event will take place. When including a 1 % suspension limit, the unloading was delayed compared to the *no suspension* case.

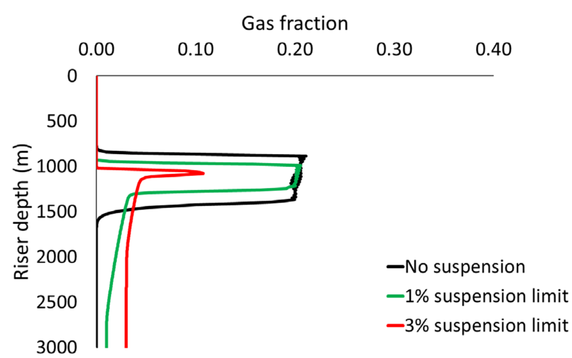

FIGURE 12: GAS FRACTION VS. DEPTH AT 7000 S (CASE 2)

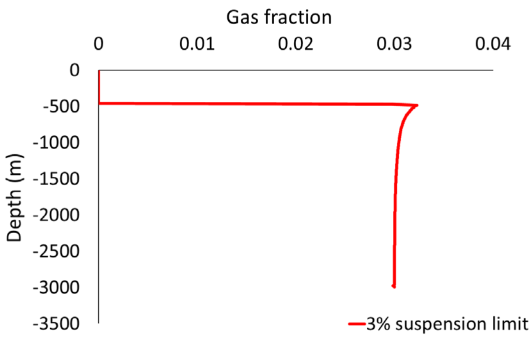

FIGURE 13: GAS FRACTION VS DEPTH AT 15000 S (CASE 2)

The simulation results presented in Case 2 shows that one needs to include suspension effects to concur field observations provided in [1, 2].

Case 3 – Comparing Kick Sizes

In Case 3, a kick is introduced at the bottom of the riser and is allowed to migrate, with pumps off. The simulation is performed considering gas inflows of 6, 8 and 10 m^3. The suspension limit is 3%. The primary goal is to determine above which kick size there is a risk of riser unloading. In Case 2, it was demonstrated that an 8 m^3 kick would not unload the riser, considering that 3% of the gas will be suspended. Any kick smaller than 8 m^3 will also be fully suspended for 3% suspension limit, but if the suspension limit is changed, the results might change. Here we show what happens when the kick size is varied. Also, a table will be presented which shows what the results would be if both kick size and suspension limit are varied. Fig. 14 shows the pressure in the bottom of the riser vs. time, and it indicates that for a 10 m^3 kick, the riser will be unloaded since the final pressure is much less than the initial one. Fig. 15 leads to the same conclusion as there is a significant increase in the pit gain for a 10 m^3 kick, showing that mud was pushed out of the well. The mud blows at the surface just after 8000 seconds after the kick has been introduced (Fig. 16) followed by the gas (Fig. 17). After the unloading, the total liquid mass in the well drops 66000 kg, which means that around 13% of the mass of mud is expelled out from the riser in the process (Fig 18). This would correspond to a drop in riser mud level of approximately 390 meters.

<u>**Suspension limit: 3%**</u>

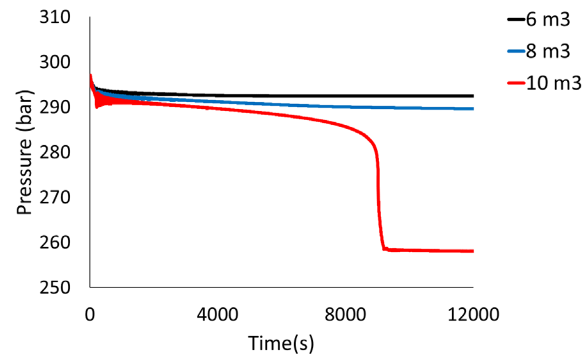

FIGURE 14: PRESSURE AT THE BOP VS. TIME (CASE 3)

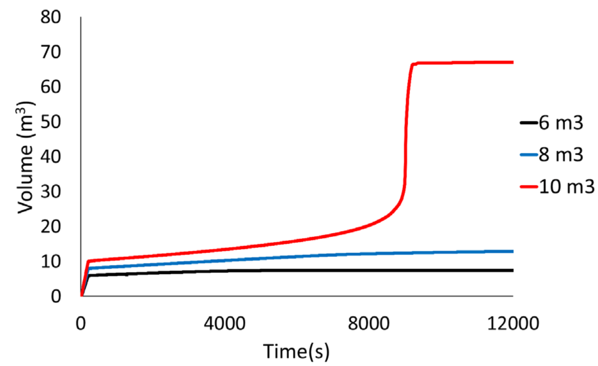

FIGURE 15: PIT GAIN VS. TIME (CASE 3)

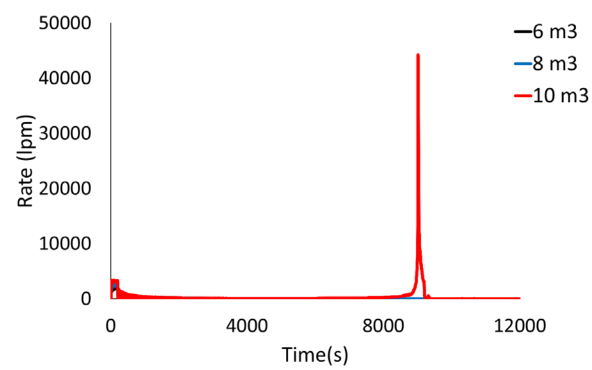

FIGURE 16: LIQUID RATE AT SURFACE VS. TIME (CASE 3)

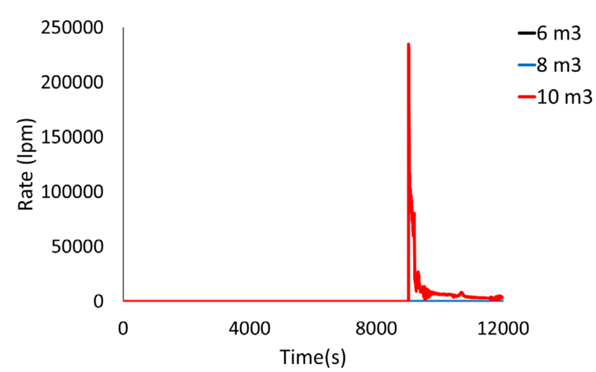

FIGURE 17: GAS RATE AT SURFACE VS. TIME (CASE 3)

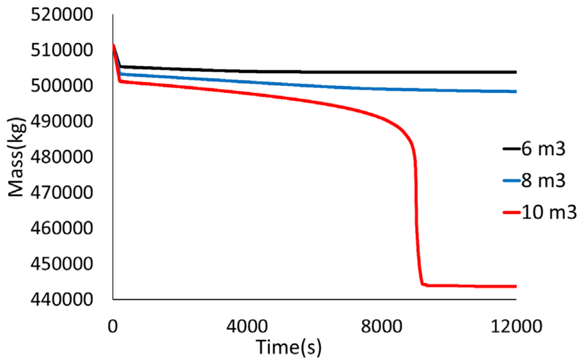

FIGURE 18: LIQUID MASS IN THE RISER VS. TIME (CASE 3)

Additional simulations were done for Case 3 changing the suspension limits to 5% and 2% to compare with the results for a 3% suspension limit (Figs. 14-18). The summary can be seen in Table 3.

TABLE 3: EFFECT OF CHANGING THE SUSPENSION LIMIT AND LEVEL OF MUD AFTER UNLOADING

Kick size	2% Suspension limit	3% Suspension limit	5% Suspension limit
6 m^3	S	S	S
8 m^3	U (-300m*)	S	S
10 m^3	U (-500m*)	U (-320m*)	S
Note: S = Suspended; U = Unloaded *Length of the riser unloaded			

As shown in Table 3, a more massive kick will increase the likelihood of an unloading event. It also shows that it is very sensitive to which suspension limits that were imposed on the gas slip model. It is clear that one needs a good model for which gas volume fractions gas suspension will take place to be able to reproduce field observations. As pointed out earlier, this will depend on the yield stress of the mud which again depends on operational conditions and pressure and temperature conditions.

As mentioned previously the second barrier is compromised when gas has been allowed to enter the riser for various reasons (trapped gas in BOP or late kick detection and response). If the kick becomes fully suspended in the riser, it has to be removed by circulation to reestablish well integrity, and it is important to evaluate how this should be done. It is also crucial to be aware of if trapped gas is present in the riser before you start circulating at a high rate creating a dangerous situation. In the next simulation case, this type of simulations will be presented.

Case 4 – Circulation of a Fully Suspended Kick

In the set of simulations performed for Case 4, first the kick is suspended, and then circulation starts. A kick of 6 m^3 is considered. The suspension limit is set to 3%. As shown in Case 3, a kick of 6 m^3 gets fully suspended, considering that a gas volume fraction of 3% will be suspended. In Case 4 the circulation starts at 6000 seconds at 20, 40, and 60 kg/s pump rates. The results are shown in Figs. 19-22. The objective is to study the impact on the maximum gas and liquid rates that can occur. As can be seen from the results, circulating the suspended kick at higher pump rates leads to higher rates at the surface. Hence, it is first essential to know if you have a suspended kick in the riser. Secondly, when displacing it, one should use a low circulation rate to reduce the consequences.

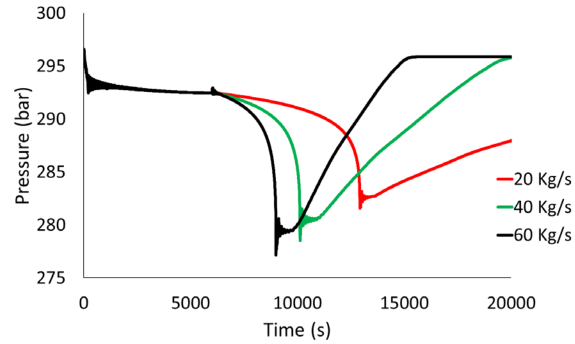

Figure 19: PRESSURE AT THE BOP VS. TIME (CASE 4)

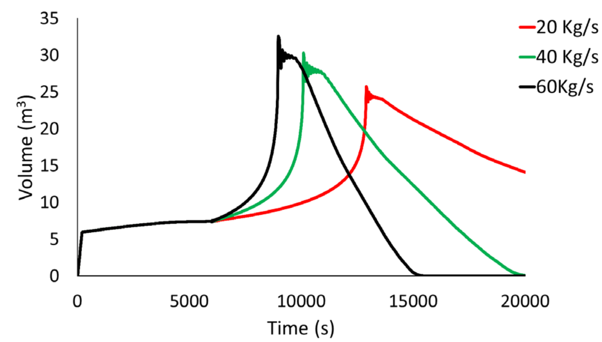

Figure 20: PIT GAIN VS. TIME (CASE 4)

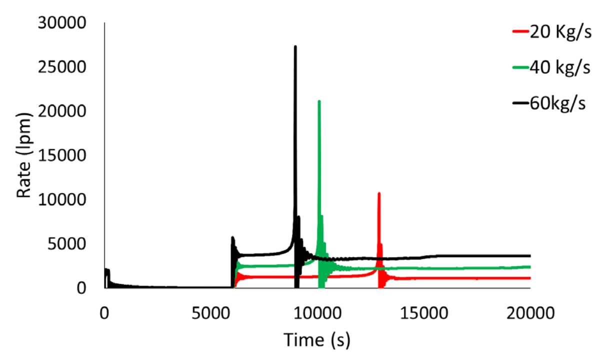

FIGURE 21: LIQUID RATE AT SURFACE VS. TIME (CASE 4)

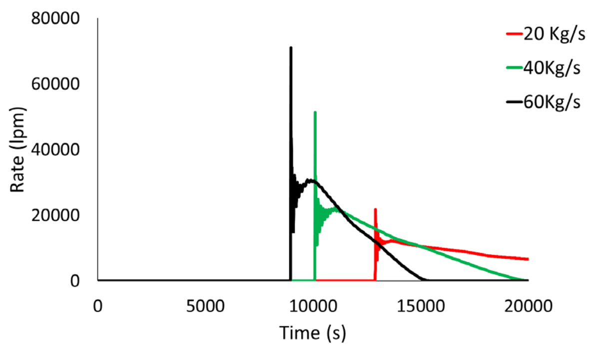

FIGURE 22: GAS RATE AT SURFACE VS. TIME (CASE 4)

It is also interesting to compare herein results with Case 1, where a 6m^3 kick is circulated from the beginning with a 3% suspension limit. The results are presented in Table 4.

TABLE 4: MAXIMUM VALUE OF CRITICAL PARAMETERS FOR EACH CASE

Case	1 (40kg/s)	4 (20kg/s)	4 (40kg/s)	4 (60kg/s)
Pit gain	60 m^3	25 m^3	30 m^3	33 m^3
Liquid rate	60000 lpm	10000 lpm	22000 lpm	27000 lpm
Gas rate	340000 lpm	20000 lpm	52000 lpm	73000 lpm

In light of these results, we reiterate the recommendation given in [8]. It is an advantage to let the gas become suspended before starting circulation to minimize the maximum gas and liquid rates. As evident from the results, after the kick is suspended, it can be convenient to use lower circulation rates because it leads to lower rates at the surface.

CONCLUSION

When considering the unloading scenario, it is essential to capture all effects that can have impact on the simulation results. The drift-flux model used here can include gas slippage that can take into account various flow regimes and include suspension effects. Also, it includes acceleration and friction effects that may have an impact. As an example, even though we have a wide riser some friction can occur when the maximum flowrates are achieved which again will have an impact on the gas expansion.

Use of the drift-flux model is expected to give more realistic and less conservative results (lower maximum rates) compared to a simpler single bubble approximation where the gas bubble is assumed to occupy the whole cross-sectional area and does not mix with the liquid region.

It has been demonstrated that the AUSMV scheme is robust enough to handle the highly transient situation that will take place during an unloading scenario. However, it was seen that it is important to ensure a broad enough interpolation interval when the gas slip parameter changes in the transition to one phase gas flow to avoid numerical problems.

For a numerical method to provide realistic results regarding which maximum rates that can occur during an unloading scenario, it is vital to reduce the numerical diffusion of the scheme. Presence of numerical diffusion will lead to underestimation of the maximum rates. In this work, it seemed that using 200 cells in the riser in combination with the use of slope limiters in the AUSMV scheme reduced the numerical diffusion to an acceptable level.

We have demonstrated how transient models can be applied for forecasting the likelihood of an unloading event after gas enter the riser and how kicks can become entirely trapped without reaching the surface. This will depend on riser geometry, kick size and suspension limit. A transient model will be able to predict which maximum rates that possibly can occur at the surface and at which time this will be expected to take place. Also, it can be used to predict how much the mud level will be reduced in the riser after the unloading scenario.

It has been demonstrated that changing the suspension limit in the model will have a significant impact on the results. It has substantial impact on the kick migration and will determine whether a kick of a given size will reach surface or not. Also, the suspension limit chosen will have significant impact on the simulation results regarding how violent the unloading will be. Hence, it is essential to have a good model for calculating how large volume fraction of gas is expected to become trapped by the mud.

It has also been demonstrated that transient models can be used to evaluate operational procedures, In Case 4, the simulation results reconfirmed the recommendation given in [8] letting the gas become suspended in the riser before starting circulation to remove it. In this case, a low pump rate should be used. By letting the gas become suspended first and then circulate at a low rate, one will reduce the maximum flow rates that can occur at the surface.

To be able to simulate the suspension process and match field experiences, there is a need for having a good model for which gas fractions this will take place. As was seen from the literature review, this will depend on the yield stress, which again depends on pressure and temperature conditions in the well, but also the operational history (circulation vs. static conditions). This needs to be integrated into a fully transient flow model that is able to capture how pressure and temperature conditions in the well change with time. For instance, the temperature profile in the riser will change when the operational situation changes from having full circulation to a long static period (cooling) which will be the case in a well control scenario. Hence, more modelling work is required to close the gap between field observations and needs, and what transient models can predict.

The method developed is well suited for doing similar calculations with oil-based drilling fluids, although additional work is required to handle gas absorption and degassing properly.

ACKNOWLEDGMENTS

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