Improved Dynamic Modelling of Two-Phase Flow in Well Control Operations

by

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Preface

This thesis is submitted in fulfillment of the degree of Doctor of Philosophy (Ph.D.) degree in the Department of Energy and Petroleum, Faculty of Science and Technology, University of Stavanger (UiS).

This research was conducted under the supervision of Professor Kjell Kåre Fjelde and Professor Dan Sui, from 31st August 2016 to 31st August 2019.

The project was funded by DrillWell – Drilling and Well Centre for Improved recovery, a research cooperation between IRIS, NTNU, SINTEF, and UIS. The research was financially supported by the Research Council of Norway, Aker BP, ConocoPhillips, Equinor, and Wintershall.

This Thesis is divided into two parts. The first one contains eight chapters: 1) Introduction, 2) Objective of the Thesis, 3) Well Control, 4) Models for Well Control Evaluations, 5) Numerical Techniques for Transient Flow Modeling, 6) Overview of the Research Papers, 7) Conclusion and Future Work, and 8) References. The second part contains six published technical papers with the research results.

Acknowledgments

I would like to express my sincere gratitude to my primary supervisor, Kjell Kåre Fjelde for his dedicated support, guidance, and encouragement throughout the process. I feel extremely lucky for having the opportunity to work with such a brilliant person. I have learned a lot with Kjell and his friendship, empathy, and sense of humor have made my Ph.D. an amazing experience. A big thanks to my co-supervisor, Dan Sui, for providing guidance and feedback throughout this project.

I would like to thank the University of Stavanger for having me and the IEP department leaders and all the staff for supporting me throughout this journey. I would also like to acknowledge SINTEF for their active guidance and engagement in the research.

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To conclude, I would also like to thank my Ph.D. fellows who have provided a lovely working environment. A special thanks to all my friends and family who supported me.

Summary

This thesis focuses on exploring applications and optimizing transient numerical models for simulating well control situations.

The main scope of the research was to find opportunity for improving existing numerical models and to improve the models accordingly. Relevant cases were constructed, simulated with different mathematical models and numerical methods, and the results were compared. The cases constructed were to a large degree motivated from challenges associated with kick handling in subsea back pressure MPD systems and gas in riser unloading events.

The models that have been used for evaluating the transient scenarios are the single bubble model and Drift-Flux model. A static analytical model was also developed for kick tolerance evaluations.

The first topic studied was kick tolerance evaluation from a probabilistic perspective, using Monte Carlo simulations. By adopting this approach, one can get a probability for whether a certain kick volume can lead to fracturing the formation in the weakest spot. It is also shown how this approach can be useful for analyzing how the uncertainties in each input parameters change the results. The Monte Carlo simulations has, to our knowledge, not been used so far for kick tolerance evaluation.

An important matter explored throughout the research was the effect of the numerical diffusion in the results when simulating well control situations and the importance of restricting this effect. We demonstrated how to use different techniques for restricting the numerical diffusion and compared the results between them.

This thesis also studies kick behavior when using subsea backpressure MPD systems with oil based mud. In this system, one need to evaluate what will be the maximum surface rates and surface pressure compared to equipment limitations when trying to circulate a certain kick volume directly through the MPD system.

The transient flow model for simulating a kick in oil based mud was provided by SINTEF Industry. This model uses the Drift-Flux formulation solved numerically by the predictor-corrector shooting technique. We have used this model to study, for instance, how the results vary when modelling the gas solubility in different ways, how changes in back pressure will impact where free gas will emerge in the riser, the effect of different kick sizes and the impact the circulation rate will have on the maximum flow rates at surface.

This thesis has also studied the unloading scenarios that can occur when free gas enters a riser filled with water based drilling fluid. Here the impact of gas suspension, kick sizes and riser geometry on the severity of the unloading was investigated.

For these investigations, the explicit AUSMV scheme was used as a numerical solver for the Drift Flux model. The gas slip model used incorporated different flow regimes as well as the effect of suspension where small gas volumes are trapped in the drilling fluid. By using this numerical scheme, we have demonstrated, for example, that the suspension limit has a significant impact on the simulation results, especially when studying whether a riser unloading event might occur or not for certain kick sizes. The suspension limit is often neglected in such models and we advocate the importance of considering this effect in flow models for simulating kicks in WBM.

Sensitivity analysis were consistently performed in the publications produced during the Ph.D. The numerical models allowed to explore a gas kick behavior during well control situations and how important parameters affect the results. The thesis also highlights the importance of selecting the appropriate models and the appropriate numerical method for simulating well control situations.

List of Papers

Paper I	Gomes, D., Bjørkevoll, K. S., Frøyen, J., Fjelde, K. K., Sui, D., Udegbunam, J. E., and Moenikia, F., 2017. *Probabilistic Flow Modelling Approach for Kick Tolerance Calculations*. Presented at OMAE 2017, Trondheim, Norway. 25-30 June. Published in the proceedings of the ASME 2017 36th International Conference on Ocean, Offshore & Arctic Engineering – Volume 8: Polar and Arctic Sciences and Technology; Petroleum Technology. OMAE2017-61391. doi:10.1115/OMAE2017-61391 (paper with review).
Paper II	Gomes, D., Frøyen, J., Fjelde K. K., and Bjørkevoll, K., 2018. *A Numerical Comparison and Uncertainty Analysis of Two Transient Models for Kick Management in a Backpressure MPD System*. Presented at the SPE Norway One Day Seminar, Bergen, Norway, 18 April. SPE-191345-MS. doi:10.2118/191345-MS.

Paper III	Gomes, D., Nilsen, M. S., Frøyen, J., Bjørkevoll, K., Lage, A. C. V. M., Fjelde K. K., and Sui, D., 2018. *A Transient Flow Model for Investigating Parameters Affecting Kick Behavior in OBM for HPHT Wells and Backpressure MPD systems*. Presented at OMAE 2018, Madrid, Spain, 17-22 June. Published in the proceedings of the 37th International Conference on Ocean, Offshore & Arctic Engineering – Volume 8: Polar and Arctic Sciences and Technology; Petroleum Technology. OMAE2018-77547. doi:10.1115/OMAE2018-77547 (paper with review). This paper yielded the first author the Subrata Chakrabarti Young Professional Award by the OOAE Award's Committee.

Paper IV	Gomes, D., Frøyen, J., Fjelde, K. K., and Bjørkevoll, K. S., 2018. A *Transient Modelling and Sensitivity Analysis of Influxes in Backpressure MPD Systems*. Presented at the SPE Asia Pacific Oil & Gas Conference and Exhibition, Brisbane, Australia, 23-25 October. SPE-192101-MS. doi:10.2118/192101-MS.
Paper V	Gomes, D., Bjørkevoll, K. S., Fjelde, K. K., Frøyen, J., 2019. *Numerical Modelling and Sensitivity Analysis of Gas Kick Migration and Unloading of Riser*. Presented at OMAE 2019, Glasgow, Scotland, 09-14 June. Published in the proceedings of the 38th International Conference on Ocean, Offshore & Arctic Engineering – Volume 8: Polar and Arctic Sciences and Technology; Petroleum Technology. OMAE2019-95214. doi:10.1115/OMAE2019-95214 (paper with review).
Paper VI	Gomes, D., Fjelde, K. K., Bjørkevoll, K. S., Frøyen, J.,2020. *Gas Suspension Effects in Riser Unloading and Appropriate Modelling Approaches*. Presented at the OMAE2020 Virtual Conference 3-7 August. OMAE2020-18049. doi:10.1115/OMAE2020-18049 (paper with review)

Abbreviations

BHP	Bottom hole pressure
ECD	Equivalent circulating density
HPHT	High-pressure high-temperature
WBM	Water-based mud
OBM	Oil-based mud
MPD	Managed pressure drilling
PVT	Pressure volume temperature
SIDPP	Shut-in drillpipe pressure
SICP	Shut-in casing pressure
MGS	Mud gas separator
RCD	Rotating control device
WBE	Well barrier element
SM	Safety margin
BOP	Blowout preventer
OD	Outer diameter
ID	Inner diameter

1 Introduction

1.1 Outline of the Thesis

This thesis is divided into eight chapters. Chapter 1 brings a brief introduction to concepts that are important for understanding the context of the research. Chapter 2 summarizes the main objectives of the thesis. Chapter 3 discusses well control. Chapter 4 presents models for well control evaluations. Chapter 5 presents numerical techniques for transient flow models such as the ones shown in Chapter 4. Chapter 6 provides an overview of the technical papers produced during the research period. Chapter 7 presents the conclusions and future work. In Chapter 8 the references are provided. Finally, the technical papers are attached.

1.2 Well Construction

An oil well is constructed to connect the reservoir and the surface to enable safe and controlled extraction of reservoir fluids. This research addresses well control issues that can occur during the well construction process. Kicks can take place in different phases of the well construction process such as drilling, tripping, running casing, among others.

Essential drilling equipment involves drillpipe, bit, safety valves, lifting system components, mud pumps, mud tanks, among others. Conventionally, a new hole is drilled by rotating the drillstring and bit. A basic drilling system and equipment are depicted in Fig.1.

Drilling rigs are used to construct the well. Proper rig selection will depend on (but not only) whether the field is onshore or offshore, the water depth (when applicable), and the loads expected. The correct selection is crucial for a safe, time-efficient, and cost-optimized operation (Mitchell and Miska 2011).

The correct choice of drilling fluid is critical. The drilling mud is pumped down the drillstring, passes the bit and ascend in the annulus back to the surface where it will be treated and circulated again. Some of the functions of the drilling fluid are maintaining the well pressure, cooling and lubricating the bit, and transporting cuttings to the surface.

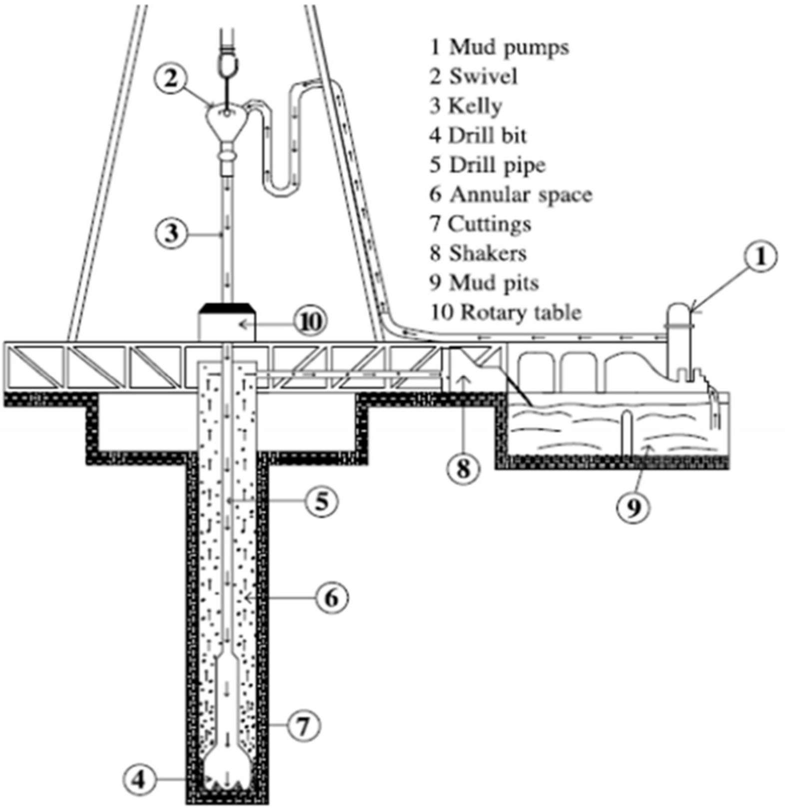


Figure 1: Drilling system (Rodriguez et al. 2004)

1.3 Operational Window

The planning of a well requires geological data that will assist in deciding the well location and the casing program, anticipating drilling problems, selecting the type of drilling mud to be used, determining the well inclination and other specific well design characteristics. A pore pressure and formation strength prognosis has to be worked out in the planning process. An example is illustrated in Fig. 2. This will define the operational pressure window and be decisive for which mud weight and flow rates can be used in the planned hole sections. This window can be quite narrow, especially for HPHT wells, and it can be difficult to stay safely within it. The mud weight will be adjusted accordingly, as also depicted in Fig. 2. The drilling mud acts as a well barrier, and if at any moment, the barrier is compromised, the well integrity is at risk. For example, if the pressure in the hole reaches the fracture pressure, there is a risk of fracturing the formation, and if it drops below the pore pressure, formation fluids can enter the well. The latter scenario is known as a kick and is classified as a well control situation. Computational modeling of such cases is the focus of this research.

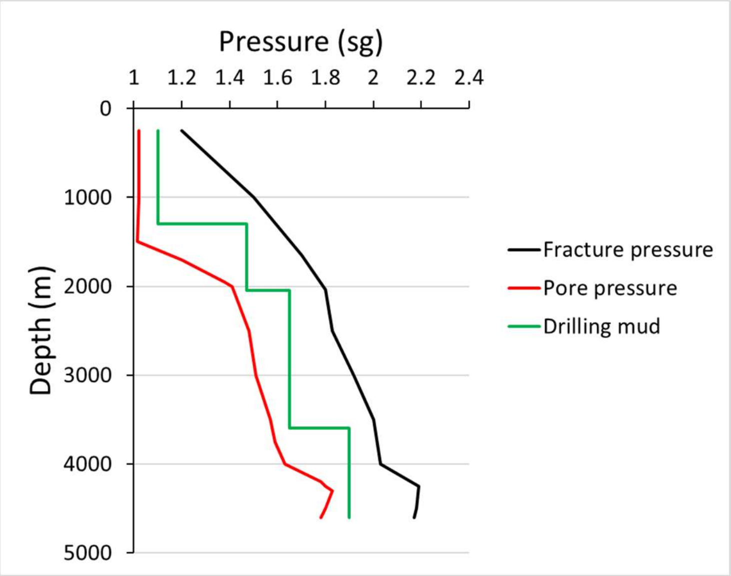


Figure 2 – Schematic of formation pore pressure and fracture pressure.

It is crucial that the rig crew can identify signs of a kick. Among the indications are changes in flow rate, changes in pump pressure, changes in the drillpipe weight, pit volume increase, and well flowing with pumps off. Assuming a hydrocarbon influx, a kick in OBM is harder to detect due to the kick solubility in the mud.

If a kick is confirmed, actions should be taken quickly to secure the well and then perform a well kill operation. In traditional drilling, the first step is to shut-in the well. The pressures are then recorded, mainly the shut-in drillpipe pressure (SIDPP) and the shut-in casing pressure (SICP). They provide useful information for kill calculations, including the density of the new mud to be pumped in the well to reestablish the well barrier and avoid additional kicks.

If not handled properly, a kick can pose a significant danger to the operation. In the worst case, the fluids can migrate to the surface, causing a massive and uncontrolled release of reservoir fluids at the surface. This situation is known as a *blowout* and can provoke explosions, loss of the rig, loss of lives, and damage to the environment.

1.4 Casing Selection and Kick Tolerance

The well is drilled in steps, by drilling holes of different diameters and securing each section by running and cementing in place a casing, to assure the well integrity. An example of a casing program is shown in Table 1. This planning will depend on the pore pressure and fracture pressure gradients. Casings act as barrier elements.

Ideally, it is desirable to set the casings as deep as possible. Nevertheless, the maximum allowable setting depth will depend on if a particular type of casing can withstand the loads it can be subjected to. Besides, the number of casings is limited. According to NORSOK D10 (2013), casings shall be designed to withstand all expected loads. This analysis needs to include potential well control situations. It is also necessary to consider, for instance, burst, collapse, and axial loads.

Table 1 – Casing program (**Paper I**).

Type of Casing	Hole size (in)	Casing size (in)	Depth from seabed (m)
Conductor	36	30	100
Surface casing	26	20	1000
Intermediate casing	17 1/2	13 3/8	2200
Production casing	12 ¼	9 5/8	4000
Production liner	8 1/2	7	4500

When planning the casing program, potential kick scenarios are considered. During the well kill operation, the BHP is kept constant equal to the pore pressure plus a safety margin. This is achieved by choke pressure adjustments. However, the pressure in the well at the casing shoe will vary when the kick is circulated from the bottom to the surface. The pressure will increase and reach a maximum when the kick is situated right below the shoe and it is necessary to ensure that the well pressure at this location does not exceed the fracture pressure of the formation at the casing shoe depth. Upon the occurrence of a kick and during circulation, the casing shoe pressure will vary according to Eq. 1, where friction is neglected.

$$\mathrm{P_{sh}} = \mathrm{P_{BHP}} - \rho_{mix} \times \mathrm{g} \times \mathrm{h} \tag{1}$$

Here, $\mathrm{P_{BHP}}$ is the bottom hole pressure, g is the acceleration of gravity, and h is the vertical distance from the influx point to the casing shoe.

The more gas inflow from the formation, the less the average mixture density (ρ_{mix}), and consequently, the pressure at the casing shoe (P_{sh}) increases. This evaluation of maximum casing shoe pressure for various kick sizes is called *kick tolerance evaluation*. If a certain kick size cannot be circulated out without risk of fracturing the formation, one will need to shorten down the planned length of the section to be drilled. It is important to highlight that the pressure profile will be different depending on whether the gas is soluble or not in the drilling mud.

Kick tolerance is essential in well design and is defined by NORSOK D10 (2013) as *“maximum influx volume that can be circulated out of the well without breaking down the weakest zone in the well.”* Usually, the weakest part in the well is the formation at the casing shoe. If the formation breaks, the mud can be lost to the formation resulting in financial losses that comprise materials, services, and additional time. Besides, the loss of fluid will decrease the mud level in the well and thus the hydrostatic pressure will be reduced, which will leave the system vulnerable to additional kicks.

In Paper I, a methodology for kick tolerance evaluation is presented. The calculation methodology combines predictions of two different flow models with the Monte Carlo method to obtain probabilistic distributions that show the probability of a certain kick size leading to formation fracture and fluid losses. The paper also uses the probabilistic approach for sensitivity analysis evaluation of critical parameters having impact on the casing shoe pressure.

2 Objective of the Thesis

This thesis provides the results of research focusing on analysis and improvement of transient flow models for simulating well control situations. To perform the evaluations mentioned above, different models have been used. SINTEF Industry has provided an advanced transient flow model using the Drift-Flux model and the predictor-corrector shooting technique. This can be used for simulating kicks in OBM and WBM. A more simplified transient flow model using the Drift-Flux model and the AUSMV scheme for numerically solving it has also been used. This code has been developed earlier at University of Stavanger but has been modified during the Ph.D. work. This flow model only handles kicks in WBM. In addition, simpler kick models based on the single bubble model concept were also developed. The scope of the thesis is listed below:

- Demonstrate the implementation of different modeling approaches for kick tolerance evaluations with special focus on how these can be combined with probabilistic modeling.
- Implementation and use of transient models to analyze different well control scenarios covering kick tolerance evaluations, kick in subsea backpressure MPD systems, kick behavior in WBM vs. OBM, gas suspension effects and riser unloading (for WBM).
- Use of sensitivity analysis to identify which physical parameters and modelling assumptions that are having most impact on the simulation results
- Compare different models and numerical methods in terms of accuracy in the prediction of flow parameters during well control. The various well control scenarios considered are used to identify potential

improvements in the modeling approach and the numerical calculations.

- Discuss the importance of restricting numerical diffusion and demonstrate its effects on the prediction of flow parameters during a well control event.
- Demonstrate how transient models can be used for providing operational recommendations and corroborating procedures.

3 Well Control

Uncontrolled kicks can develop into blowouts with catastrophic consequences such as loss of the rig, harming of the environment, and loss of lives. Examples of such accidents are the Ekofisk Bravo platform incident in the Ekofisk field, the IXTOC 1 well in the bay of Compeche (Haegh and Rossemyr 1980), the Enchova platform in Santos basin (Maduro and Reynolds 1989), and the Macondo well in the Gulf of Mexico (Sutton 2013). Those are just a few examples of accidents involving blowouts that occurred in the last decades and thus it is important to perform research related to well control.

Well control involves a set of guidelines for preventing kicks or, in case it occurs, for handling it properly to eliminate the risk of a blowout. Kicks can happen for several reasons such as unexpected gas pockets encountered during drilling, when the circulation stops for a connection (because the ECD is temporarily reduced), swabbing effects, insufficient mud weight, loss of circulation, and improper hole filling with mud during tripping. In those cases, basically what happens is that the well pressure at the point of the influx becomes lower than the formation pore pressure. The way the kick is taken can affect how distributed it becomes in the annulus. If the well is static for instance during connections or while tripping, the kick may become concentrated. However, if it is taken while circulating and rotating, the kick will become more spread out.

A sudden increase in drilling rate, increase in the pit tank, increase in the flow rate, pump pressure decrease, reduction in the drillpipe weight, and flowing well with pumps off are typical signs of a kick (Mitchell and Miska 2011, and Azar and Samuel 2007).

Figure 3 illustrates a well schematic, considering traditional drilling, in which the operations take place with an open well. Some essential well control components are depicted.

The blowout preventer (BOP) is a valve-equipped component placed on the wellhead and this can block the annular space between the well and the drillstring at any time, preventing any kick of entering the riser section and flowing to the surface. The BOP can be installed on the seabed or the rig depending on whether the well is onshore or offshore, and whether the process is carried out from a drilling vessel or a fixed platform.

The choke valve (labeled “C” in Fig. 3) is essential in well control. The choke valve can be manipulated for circulating a kick out of the system safely. Depending on the arrangement, it can be used for applying backpressure in the well. This can be used to control the bottomhole pressure (BHP).

The mud is injected at the surface and returns with cuttings that are typically removed in the shale shakers, installed before the pit tank. In case of a kick, the return flow is diverted through the chokeline to the separator (identified as “S” in Fig. 3), where the gas is removed. After all the contaminants are removed, the mud is suitable to be pumped down the drillstring again.

The pit tank holds the drilling mud ready to be pumped in the drillstring through the mud pump (identified as “P” in Fig. 3). Changes in the level of mud in the pit tank can provide useful insights on if the operation is proceeding without abnormalities. For instance, an increase in the pit gain can be an indication that a kick took place at the bottom of the well. A kick in a free gas form will provoke a more significant increase in the pit level because it will displace a volume of mud equal to the gas volume. In addition, it expands on its way up, pushing more mud out of the well. If the gas kick is dissolved in the drilling fluid, the pit gain increase will be much less.

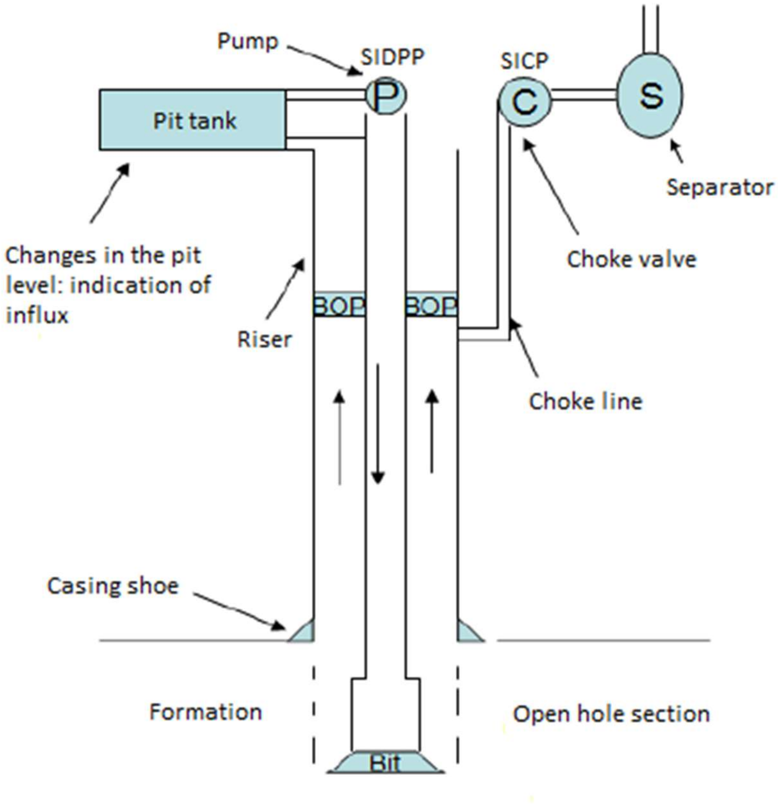


Figure 3 – Well control schematic (**Paper I**)

3.1 Well Barrier Philosophy

The oil and gas industry has adopted the well barrier philosophy to maintain well safety and integrity. A technical well barrier consists of several well barrier elements (WBE). If one of them fails, a sequence of steps must be executed to reestablish the lost barrier and return to safe operation.

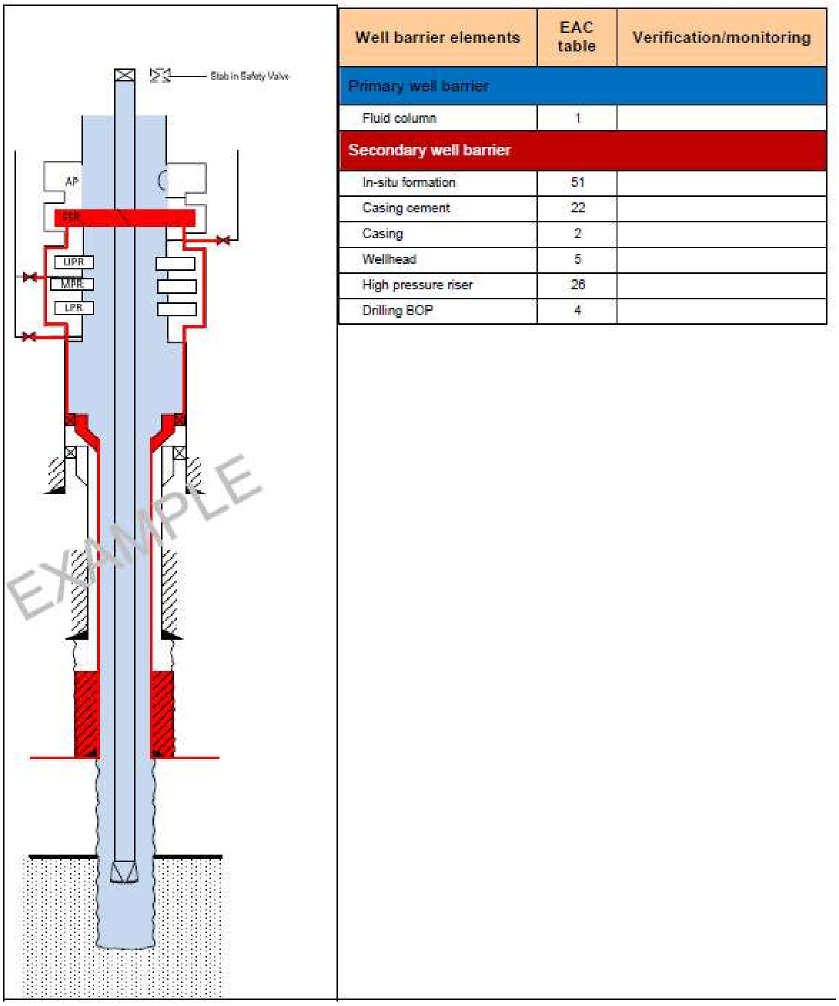
On well barrier contingency, NORSOK D10 (2013) states "*There shall be a contingency procedure which describes the steps required to re-establish a lost WBE* or *the establishment of an alternative WBE for the most likely and critical incident scenarios (e.g. kick, fluid loss, leak in intervention pressure control equipment).*"

As mentioned in Chapter one, the drilling fluid maintains the well pressure above the pore pressure, and this prevents kicks. The hydrostatic pressure exerted by the drilling mud act as a primary well barrier.

A kick event means that the primary barrier was lost and the BOP must be closed and the secondary well barrier shall be activated. Upon a kick occurrence, the BHP decreases, and when the BOP is closed, the BHP starts to increase again until the influx stops and the pressure stabilizes. If the BOP is not closed, the influx will continue to enter the well, and in the worst case, the kick can reach the surface and cause a blowout. In an offshore environment, if a kick passes the BOP it will enter the drilling riser. When the kick migrates upwards in an open well, it will experience a decrease in pressure. If the kick is in a free gas form, the gas will expand on its way up and can push a massive amount of drilling fluid above it out of the well. This phenomenon is called *riser unloading*. The decrease in the mud level in the riser can lead to a riser collapse due to the external pressure caused by the hydrostatic pressure of seawater that, in normal conditions is contra posed by the drilling mud. The reservoir fluids, if reaching surface, can also ignite, leading to explosions and consequent loss of the rig, lives, and environmental damage.

An example of well barrier configuration for a specific drilling activity is provided in Fig. 4. As illustrated, several WBE can act as a primary barrier.

Some elements can be part of both primary and secondary barriers upon compliance of specific requirements defined in the design phase.



Well barrier elements	EAC table	Verification/monitoring
Primary well barrier		
Fluid column	1	
Secondary well barrier		
In-situ formation	51	
Casing cement	22	
Casing	2	
Wellhead	5	
High pressure riser	26	
Drilling BOP	4	

Figure 4 –Example of well barrier schematic for drilling, coring and tripping with shearable string (NORSOK D10, 2013)

3.2 Conventional Well Control

In conventional drilling, the well is open to the surface during the operation, and thus submitted to atmospheric pressure. In general, if a kick takes place, some necessary steps consist in 1) shutting-in the BOP 2) waiting for the pressure stabilization 3) registering the SIDPP and the SICP 4) performing kill calculations 5) pumping denser mud and circulating the kick out. Once the kick is removed from the system, the drilling can proceed.

The well can be closed using a soft shut-in procedure or a hard shut-in procedure. The hard shut-in process consists in closing the BOP immediately after the pumps are shut down. In soft shut-in, the choke in Fig. 3 is opened, then the BOP is closed, and finally, the choke is closed again.

The procedure of removing the undesirable kick from the system is known as well kill. The kick is removed through the choke line, and the mud is replaced by a heavier mud to avoid additional kicks. The SIDPP gives information about the formation pressure and is used for calculating the density of the new mud. The SICP helps to understand the kick nature (e.g., the kick density and size). Fig. 5 illustrates the shut-in pressures.

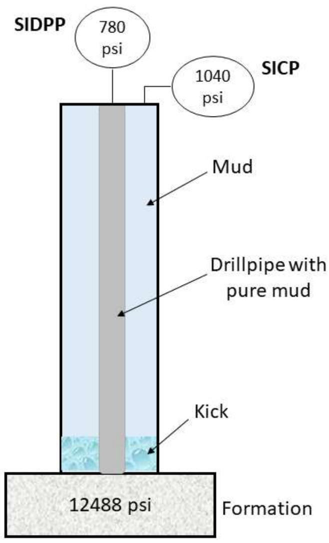


Figure 5 – Kick influx well shut-in pressures

The main kill procedures are the *driller's* method and the *wait and weight* method. In the driller's method, two circulations are needed. First, the kick is circulated out of the annulus through the choke line. Then a heavier mud (kill mud) is pumped to replace the original mud. In the wait and weight method, also known as engineer's method, the kill mud is pumped into the well, and the kick is removed through the choke line in only one circulation. Downhole casing shoe pressure and surface pressure might become lower with this method.

It is vital to keep the BHP stable at all times during drilling. The BHP should remain at a target value between the pore and fracture pressure. After the well is shut-in due to a kick, the SICP will increase until the influx has stopped due to the pressure increase. After the pressure stabilizes, the choke is opened, and the kick is circulated out. The choke adds a backpressure on the well during circulation to ensure that the BHP is kept constant and equal to the pore pressure plus a safety margin. During the kill circulation, the largest choke pressure will occur when the kick reaches the outlet and that is when the volume of free gas in the well is at its maximum. The choke can be gradually opened when the kick leaves the well, and new mud is pumped. Fig. 6 shows an example of how the choke pressure profile would be in such a scenario. One should note that during the shut-in period, a free gas kick in WBM will migrate on its own. This will lead to continuous pressure build up in the well. Here, initiation of kill circulation should not be delayed too long.

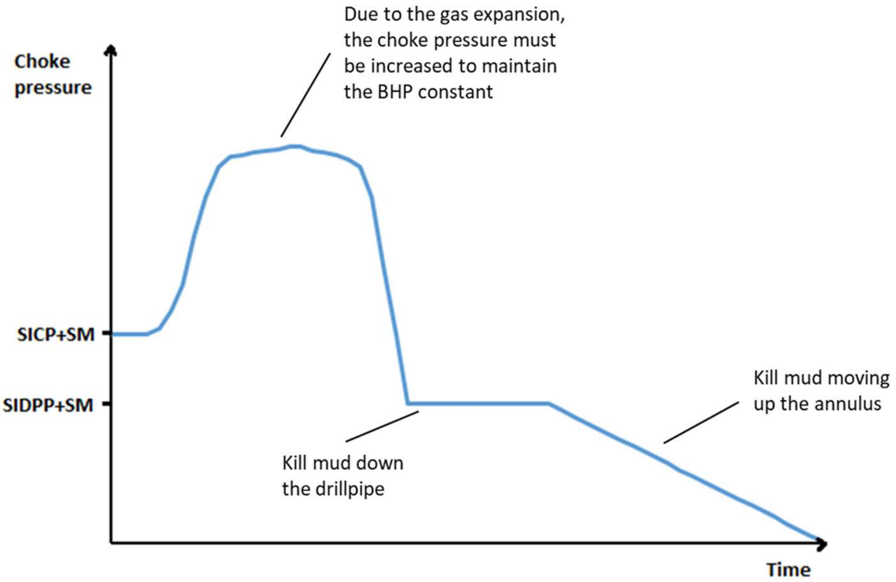


Figure 6 – Illustration of choke pressure vs. time during well control using driller’s method

3.3 Backpressure MPD Systems

Managed pressure drilling (MPD) provides means for precisely controlling the pressures in the well at all times during drilling. There are different MPD techniques as described in Gedge et al. (2013). The constant bottomhole pressure (CBHP) backpressure MPD technique, used as study case during this research, consists in installing a rotating control device (RCD) on top of the well. The RCD provides a seal between the drill string and the annulus, turning an open system into a closed system and allowing pipe movement under pressure. The system also contains manifolds, valves, and sensors that are connected with the mud circulation system. The control system can be manual, automatic, or semi-automatic.

In backpressure MPD systems, usually a slightly underbalanced drilling mud is used. At the outlet, the flow is led through a choke that is used to apply additional backpressure to the well to achieve the desired ECD. This is the same technique that is used during the well kill for conventional well control so one might look upon this as continuous well control. The concept is illustrated in Fig. 7. This system is especially useful for HPHT wells, which tend to have particular narrow operational windows where a meticulous control of the well pressures is required.

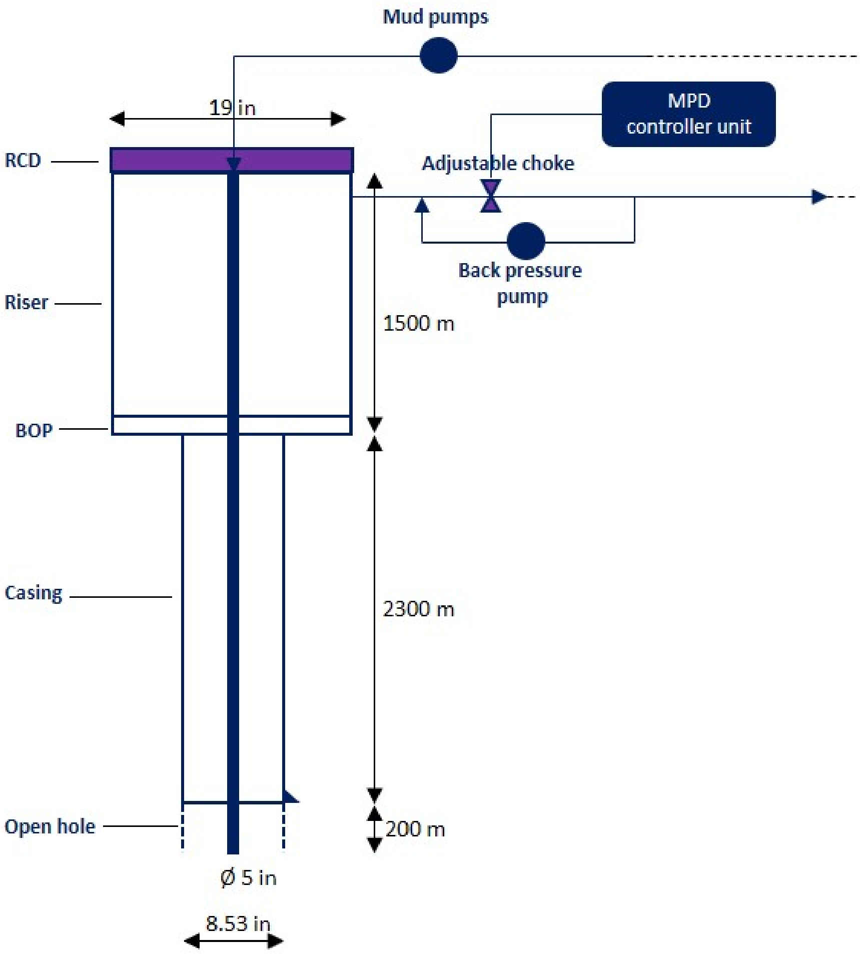


Figure 7 – Illustration of a backpressure MPD system (**Paper III**)

The backpressure MPD technique comprises a control system that monitors the flow and pressures in the system in real-time and adjusts the backpressure as needed during the whole drilling process, including tripping and connections, minimizing the risk of well control incidents. This continuous well control approach made MPD a good case study for some of our papers (**Paper II, Paper III,** and **Paper IV**).

There are several types of MPD techniques including constant bottom hole pressure (CBHP), pressurized mud cap drilling (PMCD), dual gradient (DG), HSE (return flow control), and Reverse Circulation (RC). A description of each variation can be found in Hannegan (2006a and 2006b). In our research, the CBHP type was considered. In this variant, the backpressure acts in combination with the drilling fluid to maintain a target BHP. The pressures in the well relate as per Eq. 2, taken from Hannegan (2006a).

$$EMW = MW_{hyd} + \Delta AN_{fric} + \Delta BP_{sur} \tag{2}$$

where EMW is the equivalent mud weight or effective bottomhole pressure, MW_{hyd} is the hydrostatic head pressure of the mud in the hole at the time, ΔAN_{fric} is the annulus friction pressure when circulating, and ΔBP_{sur} is the applied backpressure at the surface.

Although by using an appropriate fluid, MPD technology allows drilling in underbalanced conditions, it is important to differentiate underbalanced drilling (UBD) technique from MPD. In MPD, the surface backpressure can be used to either raise or lower the overall pressure. MPD focus on solving drilling problems and UBD, besides solving drilling problems, also focuses on reservoir performance enhancement and characterization, and additional instrumentation is needed. UBD, besides managing downhole pressure, also controls formation inflow rates used for drilling hydrocarbon-bearing formations. It should also be noted that both techniques may be used in the same well (NORSOK D10 2013 and Tønnessen et al. 2006).

The backpressure MPD system was first incorporated in fixed platforms (Reitsma and Van Riet (2005) and Nogueira et al. (2006)), and subsequently, the technology was also applied to floating platforms. Note that in Fig. 7, the riser illustrated has a larger diameter than the casing. A large riser is usually used when the drilling is done from floating rigs. The BOP is installed on the seabed, and there is a change in the flow area at that depth.

Reitsma and van Riet (2005) describes one of the first MPD field trials with an automated choke manifold. The prototype had been tested in 2003, followed by a long-term trial on a deep geothermal well. The first MPD operations with automatic influx detection and backpressure systems were performed in 2006 (Nogueira et al. 2006).

In Norway, the first automatic backpressure MPD system from fixed installations was used in 2007 (Syltøy et al. 2008). The development of a reliable automated control systems for MPD is described in Godhavn and Knudsen (2010).

The practice of adopting MPD technology to drill from floating rigs has been growing. This kind of rig is kept in place usually by mooring lines, thrusters, and a dynamic positioning system. The benefits of this application are recognized as one of the keyways to meet the necessary safety standards (Toralde 2017). This technology has allowed drilling non-drillable prospects and solved several drilling problems such as circulation loss in a deep-water well drilled from a dynamic positioning rig in Brazil in a pre-salt field, as described in Fernandes et al. (2015).

One of the advantages of using the backpressure MPD technique is the possibility of circulating small kicks through the surface MPD equipment, without the need of closing the BOP and circulating the kick out through the rig choke. When a kick is taken, the reduced hydrostatic pressure provoked by the kick can be compensated by adjusting the surface backpressure. This action will reestablish the well barrier, avoid additional kicks, save a lot of time, and prevent well control accidents, such as a blowout.

The MPD system has limitations, though. Depending on the kick size, the backpressure necessary to maintain the BHP stable can become so large that it esceeds the RCD or other equipment operational limits, causing irreparable damage. Another limitation to be considered is the volumetric capacity of the separator and the flowrates it can handle. In such cases, the kick should be removed by conventional well control procedures. According to NORSOK D10 (2013), the kick tolerance shall be specified, during the design phase, and, besides the MPD equipment limits, shall also consider factors such as the MPD system's capability of recognizing small influxes and minimizing influx volumes. MPD limitations with respect to kick handling were considered in **Paper II, Paper III,** and **Paper IV**.

3.4 Gas Kick Behavior in WBM vs. OBM

3.4.1 WBM

This research focuses on kicks composed by hydrocarbons that are gassy under standard conditions. A gas kick in WBM is considered not soluble and will displace the mud above it as soon as it enters the well, causing an increase both in the pit level and flow return of drilling mud at the surface. The pit tank level increase will be more significant as the kick move upwards and expands. The pit increase is a classical primary sign of a kick and easy to confirm in WBM, which makes kick detection easier in WBM. Liquid and gas rates at surface during the kick circulation are expected to be higher when using WBM in comparison with an OBM system for the same conditions, as ratified by simulations in **Paper II**. WBM behaves as a non-Newtonian fluid and mud properties such as viscosity, density, and gel strength are affected by downhole pressure and temperature, and are time-dependent. In a gas-liquid system, the gas travels faster than the mud, in a phenomenon known as slippage. However, the mud's non-Newtonian behavior shall also be considered since it influences the gas rise velocity, and the yield stress can hold small gas bubbles in suspension. This effect is studied in **Paper V** and **Paper VI**.

The well pressures in a closed well are also expected to be higher when using WBM. The pressure build-up, approached in section 3.2, will partly depend on the gas migration velocity. Factors such as inside and outside flow diameter, mud rheology, gas and liquid densities, rate of gas expansion, and angle of vertical deviation affect the gas rise velocity significantly (Rader et al. 1975). Johnson and White (1991) performed experiments mimicking a kick in WBM and observed, for gas concentrations higher than 10%, gas migration velocities of 100 ft/min. They also found that, for low gas concentrations, gas became suspended, with no migration. Rader et al. (1975), and Johnson and Cooper (1993) obtained similar results. Lage et al. (1994) discussed gas migration velocity in WBM based on field tests data and identified that the bubble front travels much faster than the tail. The average speed observed for the front was approximately 51 ft/min and for the rear it was about 18 ft/min. Johnson et al. (1995) provide a review on gas migration velocities and discuss how the rheological characteristics of the drilling mud leads to suspension effects where small gas bubbles get trapped in the drilling fluid. They also discuss how the gas concentration in the annulus will affect the gas migration velocity. Using the results obtained in **Paper V**, one can deduce that gas migration velocities between 64 and 74 ft/ min were found (by dividing the length of the riser by the time it took for the gas to reach the surface), for the specific conditions assumed. It was shown that this velocity depends on the suspension limit. When the gas volume fraction is lower than the suspension limit, the gas bubbles get trapped by the drilling fluid. The simulations were also able to predict that small kicks become fully trapped before reaching the surface. In **Paper VI**, it was demonstrated that the gas migration velocity will vary with the kick size, suspension limit, and riser diameter. The transient simulations also captured an interesting effect: in some cases, most of the gas becomes suspended but a small part reaches the surface without causing the riser to flow.

Slugs might rise quickly through the mud, but they tend to break up and shed a tail of small bubbles. As they ascend, they can keep breaking, getting smaller and slowing down. A combination of factors such as the mud rheology (gelling effect) and bubble sizes might result in gas being suspended by the yield stress of the mud, as discussed by Johnson et al. (1995). Since the riser has a large capacity, a huge volume of gas can be trapped. In this situation, it is imperative to strategically handle the suspended kick for avoiding this large volume of gas of reaching the surface in a way that causes severe riser unloading. In fact, according to Nes et al. (1998), this is believed to be the cause of the Zapata Lexington accident, which occurred in 1984.

The suspension phenomenon was observed in experiments presented in Johnson et al. (1995). They claimed that, in non-Newtonian fluids, small gas volumes could become fully suspended along the annulus, not reaching the surface. Another conclusion is that suspended gas affects the shut-in pressure and can lead to misinterpretations. In Fjelde et al. (2016) it was shown, by simulation, how various suspension limits will impact the pressure build up for kicks migrating in a closed well. However, the bulk of the kick is still migrating with the same velocity even if the suspension limit and pressure build up are different.

Large scale field tests were presented in Gonzalez et al. (2000), which show that kick migration in deepwater drilling risers, filled with WBM, is governed through dispersion rather than slug-type flow. The tests consisted of releasing 10, 20, 30, and 50 bbl of air trapped below the annular BOP into a 17 ¼ in internal diameter riser containing 13.2 ppg mud. The well was 3118 ft deep. They observed that the kicks got dispersed and that they could become trapped. For example, after 10 bbl of air was injected, no gas was seen at the surface for 3.6 hours, indicating that the gas was trapped. When they turned on the pump, the gas came out at surface as small bubbles.

Rommetveit et al. (2005) describe a field test in deepwater where a small kick was injected in the bottom of the riser and circulated. Also, here it was observed that the gas got dispersed, instead of moving as a slug.

3.4.2 OBM

If the drilling fluid used is OBM, the kick dissolves in the mud, and therefore volume and flow changes might be too mild to be noticed. As the gas is circulated upwards, it will experience a decrease in pressure and temperature, and eventually, the bubble point will be reached. At this point, the first few molecules of gas leave the liquid phase and form a small bubble of free gas. An additional phase (free gas) will be present from this time on. If the bubble point is reached when the kick has passed the BOP, the crew will have little or no time to act and can face difficulties, or in the worst case, a potential blowout may evolve. Especially considering that as the bubble point is reached, gas will come out of solution decreasing the overall hydrostatic pressure of the fluid column in the hole, and thus the BHP, leaving the system more vulnerable to additional kicks.

Skogestad et al. (2017) provide a methodology for predicting the amount of gas that an OBM system can dissolve (gas loading capability) based on the bubble-point curve as determined from thermodynamic equations of state calculations. The gas loading capability will depend on the pressure, temperature, and composition of the gas-fluid system.

The presence of free gas in the mud system will affect the pressures in the well and the flow rates observed at the surface. Free gas will push a volume of mud equivalent to the gas volume, causing an increase in the return flow observed at surface. Slyke and Huang (1990) discuss the behavior of kicks in OBM and provide a model for predicting how it impacts the pit gain, annular flow rate, and casing pressure. In this study, the kick was considered to contain hydrocarbons, carbon dioxide, and nitrogen. They showed that by circulating the kick through a choke and keeping the surface casing pressure above the bubble point of the system, the gas is kept in solution in the OBM.

For larger kicks, higher liquid and gas rates at surface will be seen. Large volumes of liquid and gas arriving at surface can be hard to handle. One strategy to delay the bubble point and dampen the amount of free gas that will be released from the OBM is to apply additional backpressure in the well through a choke valve, as also demonstrated in **Paper IV**. Larger volumes of gas will require more backpressure.

It is desirable to detect kick as early as possible. However, the dissolution of the kick in OBM will lead to a swelling of the mud, which, sometimes, is too small to affect significantly the flow returns or the pit tank. So, the initial kick indicators might not be perceived, and detection time can be longer. O’Bryan and Bourgoyne (1990) provided a method for estimating the swelling of OBM due to the dissolution of natural gases, calibrated with experimental data.

Linga and Torsvik. (2016) investigated kick detection capacity in two classes of base oil used in OBM for HPHT wells: mineral oil and paraffin oil. The investigation was performed under a range of pressures and temperatures relevant to HPHT conditions. A methane gas kick was considered. The experiments show that for pressures below 400 bar, the maximum gas loading capabilities vs. pressure follow a linear pattern and are quite similar. However, for higher pressures, the paraffin base oil is capable of dissolving more gas and, for pressures exceeding 450 bar, the system enters in the dense phase region. In this region, the gas solubility goes to infinity. The mineral base oil needs to be submitted to higher pressures to enter this region, and therefore it would be more advantageous in terms of kick detection capability. In other words, if a kick is taken in a mineral base oil system, is more likely that free gas will be present, since it is less likely that the system will be in the dense phase. Occurrence of free gas will make detection easier. Other relevant experiments involving kick dissolution in OBM systems can be found in O'Bryan et al. (1988), Silva et al. (2004), and Torsvik et al. (2016).

3.5 Riser Unloading

In an open well configuration, if free gas enters the riser, it will expand on its way upwards while being subjected to a pressure reduction. The volume of gas dramatically increases when approaching the surface and this will push the mud above it out of the well. The unloading causes high rates of mud and gas to blow uncontrollably at the rig. Another possible consequence is the collapse of the riser since the sudden removal of large volumes of fluid exposes the riser to an external pressure load caused by the hydrostatic pressure of seawater.

In a report regarding the Macondo accident, the U.S. Chemical Safety Board (CSB) alerts that while not all well kicks evolve into serious events, Macondo demonstrates that unmanaged ones can lead to dangerous ‘gas-in-riser’ events and blowouts. Riser unloading events, while not frequent, can be severe and result in rig and environmental damage, as well as death. CSB also recommends the industry to study riser gas unloading scenarios and to perform more experiments, and use modeling to improve understanding of this phenomenon and better manage the risk of large gas-in-riser events (CSB 2016). Different parameters which affect potential riser unloading events were discussed in **Paper V and Paper VI**.

The concept of riser equilibrium can be important for understanding riser unloading. When handling a gas kick in the riser with the BOP closed, the gas in the riser will expand until its pressure equals the hydrostatic pressure of the mud column above it, plus any applied backpressure. Buoyancy or slip will cause the gas to migrate, which in turn will cause further expansion. The riser equilibrium point is the point where the pressure of the gas can no longer be balanced by the pressure acting from above (mud column). Then the gas will rapidly unload all fluid above the gas (Velmurugan et al. 2016). The effect of this expansion on the fluid level in the marine riser is as follows:

$$\Delta_{mud} = H_{gas} \tag{3}$$

$$H_{gas} = \frac{V_{gas}}{C} \tag{4}$$

Where Δ_{mud} is the drop in the mud level in the riser, H_{gas} is the final gas column height, V_{gas} is the gas volume, and C is the annulus capacity.

The occurrence of riser unloading depends on factors such as the solubility of the gas in the mud, the influx size, flow patterns, and others. In addition, a significant amount of gas can become suspended in WBM along the riser

(Johnson et al. 1995). When drilling in ultradeep water, the chances of having gas passing through the BOP and into the riser before detecting the kick is more substantial than for traditional wells (Lloyd et al. 2000).

Field tests have shown that part of the gas kick can be suspended in WBM. In this case, the kick will only reach the surface if the mud is circulated (Gonzalez et al. 2000, Rommetveit et al. 2005). The tiny suspended bubbles, when circulated up, will expand and can agglomerate forming slugs that can rise rapidly close the surface, unloading the riser. The suspension limit will depend on the mud rheology and reflects the percentage of gas that will be trapped by the mud, in volume. The simulations presented in **Paper VI** shows how different suspension limits affect the severity of the unloading. For instance, the riser unloading tends to be more severe for smaller suspension limits. For a higher suspension limit it is less probable that the kick will reach the surface.

If a kick is detected after it has passed the BOP, it will be useful for the crew to know when the gas can be expected at the surface. The gas migration velocity will depend on the fluid densities, drilling mud rheology, gas solubility, among others. The studies that have been done so far diverge in the findings. To mention two examples, Johnson et al. (1995) performed an experimental study and concluded that for gas concentrations higher than 10% the gas migrates typically at 100 ft/min. In the field test published by Gonzalez et al. (2000), for the case where 50 bbl of air was injected under the BOP, the first slug capable of provoking riser unloading migrated at 4.6 ft/min.

The only way to avoid the entrance of a kick into the riser is to isolate it before the BOP and circulate it through the choke line. A kick can pass the BOP due to late detection of the kick which is especially challenging in OBM. Gas can also enter the riser after a regular well kill procedure because part of the kick can become stuck in the subsea stack after closing the BOP. After circulating the kick through the choke line and re-open the BOP to continue drilling, the gas once confined can migrate into the riser.

Santos et al. (1991) developed a mathematical model to simulate and analyze the pressure behavior during gas removal from a marine riser, through the lower portion of the marine riser to displace the gas up and inside the riser diverter system, in an attempt of avoiding riser unloading. The results indicated that in deepwater drilling, it is not advisable to allow the gas to be circulated out through the diverter system. It was also indicated that when the gas approaches the surface it pushes the mud out of the diverter system.

Lloyd et al. (2000) studied gas-in-riser situations in WBM considering riser depths of 500 to 7500 ft. The results show that it is possible to avoid a very rapid depressurization and the subsequent rapid gas expansion with riser unloading by using a slow circulation rate because it helps the gas to be dispersed which is preferable compared to having a massive slug of gas arriving at the surface.

Velmurugan et al. (2016) proposed a mathematical model to investigate the dynamic behavior of gas expansion in marine risers both in OBM and WBM. The model is based on the single bubble concept where the kick occupies the whole cross-section area. The free gas rise velocity is approximated using values for Taylor bubble. The model can estimate the equilibrium point and time of arrival of the kick at surface. Dispersion and suspension limit are not considered.

An efficient way of controlling a kick in the riser is by applying backpressure. Backpressure can be used to avoid the otherwise violent expansion of gas as a kick is being circulated out of the riser, therefore avoiding riser unloading and blowouts. Yuan et al. (2017) presents a multiphase model used for studying gas- in riser events, including riser unloading, water-hammer effect upon riser shut-in, the behavior of kick in different muds, and show how application of backpressure can help to control a gas in riser situation and avoid riser unloading.

4 Models for Well Control Evaluations

4.1 Use of Transient Flow Models in Well Control Evaluations

Multiphase flow is commonly observed in the petroleum industry. A multiphase flow system can be quite complex, and it is necessary to develop a mathematical model that describes it adequately to analyze and design a multiphase system. This research focuses on the two-phase flow that represents a kick in an annulus filled with drilling mud.

The flow models are postulated on the existence of different flow regimes during the kick ascension: either migrating on its own or being circulated towards the surface. Flow regimes are associated with how the gas is distributed in the liquid phase. For example, gas might be present as small bubbles in the bottom of the well or riser. As the gas rises, those bubbles will expand and coalesce, becoming slugs and then possibly develop further into annular flow. Examples of flow regimes in a vertical pipe are illustrated in Fig. 8. The gas tends to flow faster than the liquid. A mechanistic model for predicting the behavior of two-phase flow in an annulus is provided in Lage and Time (2000). They also offer a literature review on flow patterns which can occur.

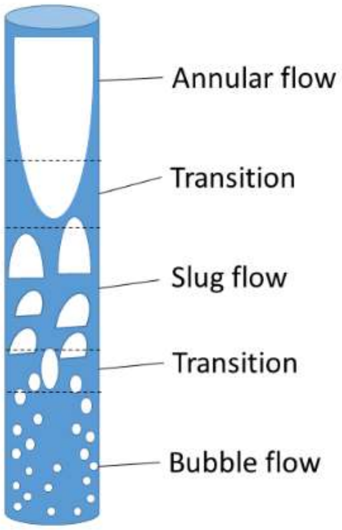


Fig. 8 – Illustration of bubble flow, slug flow, and annular flow in a vertical pipe.

Simulators that can predict pressure, gas and liquid flow, and volumes during well control procedures use specific flow models. Predicting a system behavior permits a safer and more efficient well design. Also, by simulating different well control scenarios, one can derive well control contingency plans. Simulations can also be used for training and following up of operations in real-time. The main components of such simulator are provided in Fig. 9. First, it is necessary to define a mathematical formulation comprising conservation and closure laws to describe the phenomenon. Then a solution method needs to be chosen. The set of equations is usually solved numerically. The results can be presented in different forms such as tables or plots, showing the variation of parameters with time (in case of transient models) or with depth (for instance the gas fraction along the riser after a specific period).

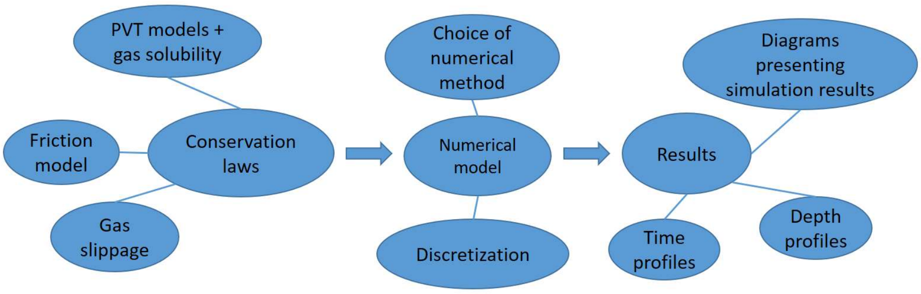


Figure 9 – Main components of a simulator.

There are several commercial simulators available to simulate kick behavior during a well control scenario. However, in commercial software, the calculation process is a “black box” which means that the user does not have access and cannot modify the underlying mathematical model with closure laws or the numerical solution method. Flow models have been developed and improved for decades. Some relevant ones will be cited next. Many of them are based on the Drift-Flux model, which consists of one conservation of mass equation for each phase and one combined conservation of momentum equation. The Drift-Flux model was adopted in the papers produced throughout the Ph.D. research and will be detailed in section 4.3.

4.1.1 Flow Models

Ekrann and Rommetveit (1985) presented a gas kick simulator, known as RF kick simulator. The governing equations here are three mass conservation equations (mud, free gas and dissolved gas) and a combined conservation of momentum equation. The numerical solution applies discretization, predictor-corrector shooting technique, and front tracking techniques. White and Walton (1990) presented a model formulated similarly in terms of governing equations but to solve them an implicit finite difference scheme, known as Wendroff's implicit scheme, is used.

Lorentzen and Fjelde (2005) presented different numerical methods for studying the Drift-Flux model and techniques for reducing the numerical diffusion. Petersen et al. (2008) showed a model that comprises seven mass conservation equations (mud, free gas, dissolved gas in mud, free formation oil, dissolved formation oil in mud, dissolved gas in formation oil, formation water, and cuttings) and a combined conservation of momentum equation. They also included a dynamic temperature model. The papers mentioned above are relevant for this research as they describe flow models and numerical methods adopted in this research. More examples of models for simulating kicks can be found in Ma et al. (2018), Avelar et al. (2009), Michael et al. (2017), Yin et al. (2017) and Xu et al. (2019).

4.1.2 Applications

Transient models are necessary to study dynamic situations such as a kick propagating in an annulus. One application involves kick tolerance evaluations for casing design. In **Paper I**, this application is demonstrated. Here, pressure variation with time was obtained, considering the formation at the last casing shoe being the weakest point. It is also shown that the results would highly depend on the kick concentration. For instance, when using the single bubble model, which considers a fully concentrated kick, higher pressures are predicted than if the kick is assumed to be dispersed in the mud.

Paper II, **Paper III**, and **Paper IV** demonstrate how to use transient models to perform kick tolerance calculations in MPD systems, for both OBM and WBM. The required choke pressures are compared against MPD surface equipment limitations to determine whether a kick of a specific size can be circulated through the MPD system without damaging the equipment. Another limitation to be considered is the mud gas separator (MGS) capacity. This limitation applies both for MPD and conventional drilling. One can evaluate this by analyzing the maximum flow rates (predicted by the simulations) to occur during the circulation of a kick of a specific size. Another example of how transient models can be used for evaluating which kick sizes are manageable through a particular MPD system is provided in Gabaldon et al. (2017). Here, the results are displayed graphically using the influx management envelope (IME) concept.

A transient flow model can also be used for studying gas suspension in WBM, as shown in **Paper V** and **Paper VI**. It is evidenced that, when fixing the suspension limit, there is a threshold of kick volume below such that the kick can become fully suspended in the riser and not able to reach the surface by pure migration. For more massive kicks, the riser will be unloaded and, the larger the kick, the more mud will be pushed out of the riser, resulting in a reduced mud level, increasing the unloading severity and risk of riser collapse. The only way of removing a suspended kick from the system is by circulating it out. It is demonstrated that, for removing a kick in this condition, it is an excellent strategy to wait for the kick to become suspended and then circulate it out at reduced pump rate. Reducing the pump rates will reduce the maximum pit gain and liquid and gas rates at the surface. This result confirms the conclusion of Marsh and Altermann (1988).

Fjelde et al. (2016) presented a transient flow model for simulating gas-liquid flow using the Drift-Flux model considering WBM. The model is used for showing how the parameters used in the gas slip relation influences the pressure build-up when a kick migrates in a closed well. The effect of gas suspension was also demonstrated. Another focus was to demonstrate the impact of numerical errors on the results, which was proven to be quite substantial.

A kick can be fully dissolved in OBM, making kick detection more challenging in OBM than in WBM. Also, in OBM, there is a higher risk of circulating an undetected kick that can rapidly come out from the solution close to the surface and unload the riser in traditional drilling. As thoroughly discussed by Yuan et al. (2017), this problem can be mitigated by adopting MPD technology. In **Paper IV**, simulations were used to study the kick dynamics in a backpressure MPD system with OBM. It was demonstrated how the application of additional surface pressure could dampen the amount of free gas released from the mud and shift the bubble point upward in the riser. It is possible to determine when and where the gas is expected to boil out from the solution. Applying backpressure will also reduce the maximum gas and liquid rates observed at the surface.

4.2 Single Bubble Model

The first mathematical model to simulate a kick was proposed by LeBlanc and Lewis (1968), and it is known as the single bubble model. This model considers that the gas occupies a whole cross-sectional area of the annulus, as depicted in Fig. 10. Up to this day, the single bubble model is a reference and often used for developing models and for comparison, as can be seen in Johnson et al. (1995), Rommetveit et al. (2005), and Gabaldon et al. (2017). This model is considered to give a conservative estimation, as shown by Larrison (2016). In **Paper I** and **Paper VI,** a transient flow model based on the Drift-Flux approach and the single bubble model were compared. It is shown that the single bubble model indeed provides more conservative results.

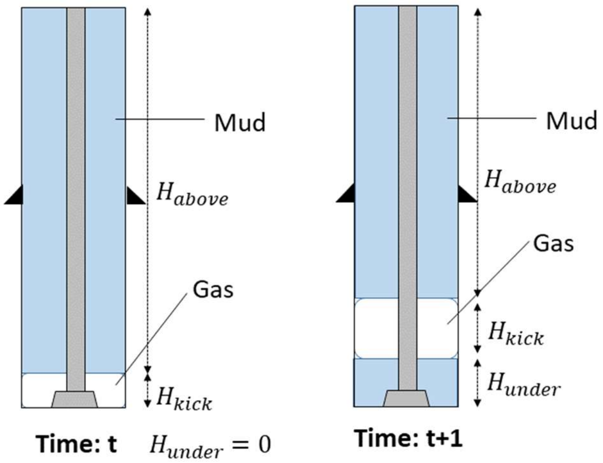


Figure 10 – Single bubble illustration.

A formulation of the single bubble model can be found in Aarsnes et al. (2016), where the single bubble assumption is used in the mathematical model for simulating gas-in-riser. The model is valid for conventional drilling, controlled mud level, and MPD with backpressure. Velmurugan et al. (2016) also describe a single bubble model that is used for simulating gas migration in marine risers. The model presented is valid until reaching the riser equilibrium point where the riser becomes instantaneously unloaded.

The transient single bubble model used in **Paper I** for simulating a kick being circulated upwards in a well is summarized in Eq. 5-13. A vertical well configuration is assumed. Because of gas expansion, the height of the kick will increase with time. The variables are updated according to the formulas below for every time step.

$$H_{under} = \frac{Q_{mud} \times time}{A} \tag{5}$$

where H_{under} is the height of mud below the kick and Q_{mud} is the mud pump rate, A is the flow area, and $time$ is the current time.

$$P_b = P_{BHP} - \rho_{mud} \times g \times H_{under} \tag{6}$$

where P_b is the pressure at the gas bubble, P_{BHP} is the bottom hole pressure, ρ_{mud} is the mud density, and g is the gravity acceleration. Note that it is assumed that the pressure at the gas bubble is the pressure at the tail of the bubble.

$$V_{kick} = \frac{P_{BHP} \times V_{bottom} \times Z(\gamma_g, P_{BHP}, T_{bottom}) \times T_b}{P_b \times Z(\gamma_g, P_b, T_b) \times T_{bottom}} \tag{7}$$

where V_{kick} is the kick volume in situ, T_{bottom} is the temperature at the bottom of the well, T_b is the temperature at the bubble (in situ), γ_g is the gas specific gravity, and Z is the compressibility factor calculated using the Dranchuk and Abou-Kassen correlation (Ghedan et al. 1993).

$$H_{kick} = \frac{V_{kick}}{A} \tag{8}$$

where H_{kick} is the height of the kick in situ.

$$H_{above} = L_{well} - H_{kick} - H_{under} \tag{9}$$

where H_{above} is the height of mud above the kick, and L_{well} is the well depth.

$$H_{top} = H_{kick} + H_{under} \tag{10}$$

where H_{top} is the depth where the top of the kick is located.

$$\rho_{kick} = \frac{M \times P_b}{R \times T_b \times Z(\gamma_g, P_b, T_b)} \tag{11}$$

where ρ_{kick} is the gas density, M is the gas molar mass, and R is the universal gas constant.

With the updated variables, one can calculate the casing shoe pressure or the choke pressure and obtain pressure profiles over time. Note that the friction is neglected in the equations presented here. During kick circulation, the bottomhole pressure will be kept constant at a certain value above the pore pressure. From this, we can the estimate the pressure at the casing shoe by the following formula:

$$P_{cas} = P_{BHP} - (H_{above} - L_{cas}) \times \rho_{mud} \times g - H_{under} \times \rho_{mu} \quad \times g - H_{kick} \times \rho_{kick} \times g \qquad (12)$$

where P_{cas} is the pressure at the casing shoe. This formula is valid until $(H_{above} - L_{cas})$ becomes negative (when top of kick has passed the shoe), L_{cas} is the casing shoe depth.

$$P_{choke} = P_{BHP} - (H_{above} + H_{under}) \times \rho_{mud} \times g - H_{kick} \times \rho_{kick} \times g \qquad (13)$$

where P_{choke} is the choke pressure at the surface, adjusted to keep the BHP constant.

The assumption of a single bubble fully occupying a certain length of the annular space provides simplified formulas for estimating worst-case scenarios that can occur during a well control situation. This model does not consider the different flow patterns that will occur because it does not account for any dispersion of the kick in the mud (kick concentration equals 1). In addition, there is no consideration of slippage, and the gas end velocity will be defined by the pump rate. The single bubble model was also considered in **Paper VI** where riser unloading was considered. In this case, the bottomhole pressure varies with time. Hence, other solution strategies must be used in this case. Two different solution methods are presented in this paper.

4.3 Drift-Flux Model

The 1D Drift-Flux model, adopted for this research is obtained by simplifying the more fundamental two-fluid model. The model consists of one equation of mass conservation for each phase and one combined equation for the momentum conservation. To provide enough equations to make the system solvable, a set of closure laws has to be provided. This includes PVT models, gas slippage, and friction pressure loss. The model was implemented using Matlab software. An example of the governing equations and sub-models for a kick in an OBM system are provided next. A more detailed description can be found in **Paper III**.

Conservation of mass of drilling mud:

$$\frac{\partial}{\partial t}(A\alpha_l\rho_l) + \frac{\partial}{\partial z}(A\alpha_l\rho_l v_l) = A\dot{m}_g \tag{14}$$

Conservation of mass of formation gas:

$$\frac{\partial}{\partial t}\left(A\alpha_g\rho_g\right) + \frac{\partial}{\partial z}\left(A\alpha_g\rho_g v_g\right) = -A\dot{m}_g + q_g \tag{15}$$

Conservation of mass of dissolved gas:

$$\frac{\partial}{\partial t}\left(A\alpha_l x_{d,g}\rho_l\right) + \frac{\partial}{\partial z}\left(A\alpha_l x_{d,g}\rho_l v_l\right) = A\dot{m}_g \tag{16}$$

Conservation of mixture momentum:

$$\frac{\partial}{\partial z}(Ap) = -\frac{\partial}{\partial z}\left(Ap_{fric}\right) - A\rho_{mix} g cos\theta \tag{17}$$

where subscript g and l represents gas and liquid (mud) respectively. The subscript mix represents a mixture property, A is the cross-sectional area, v is velocity, z is the spatial dimension, t is time, α is the volume fraction, g is the gravity acceleration, θ is the angle of inclination, $p_{fric}$is the frictional pressure loss gradient, ρ is density, $\dot{m}_g$ is the rate of gas dissolution in the mud, $x_{d,g}$ is the mass fraction of dissolved gas. The acceleration terms have been removed in Eq. 17.

To be able to solve the Drift-Flux model, one needs more equations to ensure that the number of independent variables equals the number of equations. With this purpose, the following closure laws were used:

$$\alpha_g + \alpha_l = 1 \tag{18}$$

Mixture density:

$$\rho_{mix} = \rho_l \alpha_l + \rho_g \alpha_g \tag{19}$$

It is assumed that the OBM consist of base oil, weight material and a smaller fraction of water. However, it is considered that the gas does not dissolve in water, only in the base oil. The mud density is given in Eq. 20 below:

$$\rho_l = \frac{1+x_{dg}}{\frac{x_0+x_{dg}}{\rho_o}+\frac{x_w}{\rho_w}+\frac{x_{wm}}{\rho_{wm}}} \tag{20}$$

where x_o, $x_w,$ and x_{wm} are the mass fraction of oil, water, and weight material respectively $(x_o + x_w + x_{wm}=1)$. $\rho_o = \rho_o(p, T, x_{dg})$ is the oil density, $\rho_w = \rho_w(p, T)$ is the water density, ρ_{wm} (assumed to be constant) is the density of weight material and T is the temperature in Kelvin.

Assuming that the kick consists of pure methane, the gas density is given below.

$$\rho_g = \frac{M_{CH_4} \cdot p}{R \cdot T \cdot z(\gamma_g, p, T)} \tag{21}$$

where M_{CH_4} is the molar mass of methane, R is the universal gas constant, z is the compressibility factor, $\gamma_g = M_{CH_4}/M_{air}$ is the gas gravity of methane and M_{air} is the molar mass of air.

Different PVT models can be used. A PVT model is needed to describe how gas will be dissolved in OBM and when free gas is expected to be released. Therefore, the choice of the PVT model will impact the results. In **Paper III,** two different PVT models are compared: one compositional and one correlation-based. The correlation model is based on empirical data, while the compositional model is derived from thermodynamic principles. The results show that the compositional model calculation gives a smoother transition from dissolved to free gas than the correlation model. The pit volume obtained during a kick circulation with the compositional model is lower in the beginning when most of the gas is dissolved but goes a bit higher towards the end of the simulation when the kick reaches the surface. One possible explanation for the smoother behavior seen with the compositional model is that gas absorption and degassing are more dependent on the local fraction of dissolved gas than the correlation-based model. In addition, the two models gave different results regarding at which depth free gas will occur. The compositional model tended to predict emergence of free gas deeper in the well than the correlation-based model.

It is very common to assume that when kick takes place in OBM, the influx is instantly dissolved. However, the process of gas dissolution and boiling is time dependent and it is recommended to embrace PVT models with kinetics to include these effects (Bjørkevoll et al., 2018). The Drift-Flux solved by the predictor corrector shooting technique used in this Ph.D. has the particularity of considering the gas dissolution dynamics in OBM instead of considering instant dissolution as other similar models.

The simplified frictional pressure loss model used in **Paper III** is given by:

$$F_{fric} = \frac{2f\rho_{mix}v_{mix}|v_{mix}|}{(d_{out}-d_{in})} \tag{22}$$

where f is the friction factor, v_{mix} is the mixture velocity and d_{out} and d_{in} refers to the inner diameter of the well and the outer diameter of the drillpipe.

$$v_{mix} = v_l\alpha_l + v_g\alpha_g \tag{23}$$

Since a mixture momentum equation is used, the missing information is supplied by using the following gas slip relation (Zuber and Findlay 1965):

$$v_g = Kv_{mix} + S \tag{24}$$

where K and S are flow regime dependent parameters. This model describes how free gas migrates relative to the mud.

K is the distribution coefficient and represents how the gas is distributed across the annulus. S is the drift velocity and represents the gas velocity relative to the liquid phase. For no-slip conditions, K is 1, and S is 0. This is the case when gas is suspended in the mud. Models for obtaining K and S for different flow regimes and geometrical configurations are presented in, e.g., Lage (2000) and Hasan et al. (2007).

The parameters K and S will be different for each flow pattern. In **Paper II,** K=1.2 and S=0.55 m/s were assumed mimicking typical slug flow values. The transition from slug flow to one-phase flow (gas) was done using a smooth transition using the interpolation technique. In **Paper II**, it was shown that the way of performing this interpolation would influence the results. In **Paper V** and **Paper IV,** a more advanced model for calculating K and S for various flow patterns was considered including both suspended gas (no slip), bubble flow, slug flow, and the transition to pure gas phase flow. It seems to be important to ensure sufficiently smooth transition to one-phase gas flow to avoid numerical problems. In general, one must ensure a smooth transition between the various flow patterns.

5 Numerical Techniques for Transient Flow Modelling

As stated previously, a mathematical model must be solved by an appropriate numerical method. Taking as an example two-phase flow in a vertical well modelled with the 1D Drift-Flux model, the solution can be found by first discretizing the well and then choosing either an explicit or implicit numerical strategy. When a direct computation of the dependent variables can be made in terms of known quantities, the computation is said to be explicit. When coupled sets of equations define the dependent variables, the numerical method is said to be implicit. In this case, for instance, either a matrix solver or an iterative technique is needed to obtain the solution. Two numerical techniques for solving the Drift-Flux model were adopted in this research: the AUSMV scheme (**Paper II**, **Paper V** and **Paper VI**), and the Predictor Corrector Shooting technique (**Paper I**, **Paper II**, **Paper III**, and **Paper IV**). The AUSMV is an explicit scheme where the variables are updated in time based on variables from the previous time level. It also requires knowledge of the sonic wave propagation speed in the fluid mixture. The second method is an implicit, predictor corrector shooting technique which is based on iteration.

When trying to solve systems of conservation laws numerically, there can be problems. For instance, for discontinuous solutions, a finite difference discretization of the partial differential equations is inappropriate. Indeed, if discontinuous solutions are computed using standard methods that assume smooth solutions, the numerical results will likely be flawed (LeVeque 1992).

Numerical diffusion is a relevant source of error in computational fluid dynamics (CFD). Numerical diffusion is the tendency for transported variables to diffuse abnormally. Compared to exact solutions with diffusion terms (viscosity, mass diffusivity, etc.) that are physically realistic, the numerical diffusion is an error that adds to this diffusion, smearing out the result. Numerical diffusion is more prominent when the first-order discretization is used (Hirsch 2007 and Andersson et al. 2012).

To minimize numerical errors, one can use a high-resolution method. According to LeVeque (1992), a high resolution method is able to resolve discontinuities without oscillations and without too much numerical diffusion. One can choose a high order method and make improvements to it, adapting it to the problem of interest.

Numerical errors can be quite significant. Fjelde et al. (2016) demonstrated that numerical errors could be of the same magnitude as the uncertainty provided by the mathematical model itself when considering the Drift-Flux model and prediction of pressure buildups for a kick migrating in a closed well.

To apply the conservation laws and closure relations, it is necessary to divide the well into a certain number of cells. This process is known as discretization. The equations will be solved for each cell, propagating the solution forward in time. The imposed boundary conditions must be taken into account. The larger the number of cells, the more accurate the results can be expected to be. However, increasing the number of cells will require considerably more computational time.

5.1 Predictor Corrector Shooting Technique

The predictor corrector shooting technique is described in **Paper I** – **Paper IV**. The basic idea is to start the calculation at the inlet of the discretized computational domain by guessing for the inlet pressure. Then one calculates cell by cell until reaching the other boundary. The calculated value at the outlet is then compared against the physical condition. If the deviation is not acceptable, a new and improved guess is made for the guessed inlet boundary value and the calculation process is repeated. In practice, the shooting technique reduces the problem to finding the root of a function that represents all the calculations from the inlet to the outlet and depends on the guessed variable.

An example of an application of the shooting method can be seen in Petersen et al. (2008). Here, the governing equations are solved by a finite difference method, simulating flow in a drilling environment. The RF kick simulator presented in Ekrann and Rommetveit (1985), also used a predictor corrector shooting technique. A description can also be found in Lorentzen and Fjelde (2005).

In our discretization approach, the inlet is considered at the bottom of the well (or riser) or at the pump and the outlet at the surface. For example, if the outlet pressure is given, inlet pressure is guessed, and the program solves the conservation and closure laws, from the bottom to the top, for each cell until the surface is reached, as illustrated in Fig. 11. The stop criteria will be when the calculated outlet pressure matches the boundary condition within a predefined tolerance. If the tolerance requirement is not satisfied, an improved guess for the inlet pressure is made.

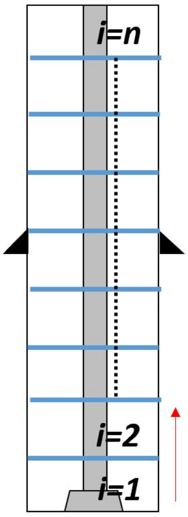
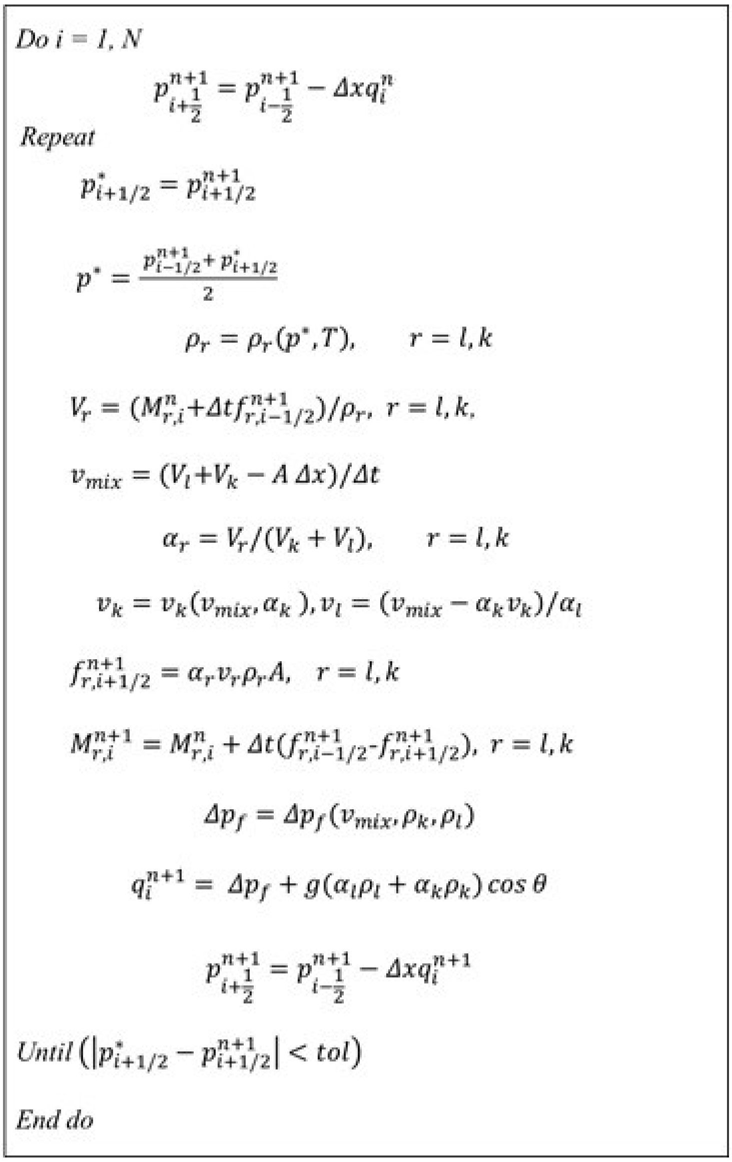


Figure 11 – Illustration of Shooting technique application in a discretized well.

For each cell, the inlet pressure and mass fluxes are known. Then, an estimate of the downstream pressure is made and the average cell pressure is used to find the outlet mass fluxes and update the mass distribution in the cell at the new time level. Then an improved estimate of the downstream pressure is made and the mass calculation is repeated. This process can be repeated until the calculations converge for each cell. The iteration across the cell itself is the predictor corrector process. An illustration of the solution algorithm is given in Fig. 12 taken from **Paper I**.

The following algorithm (Fig.12) shows the predictor-corrector shooting technique. The outer loop advances through the boxes. For each box, there is an iteration which updates the mass distribution in the cell (repeat /until).



```
Do i = 1, N
    $p^{n+1}_{i+\frac{1}{2}} = p^{n+1}_{i-\frac{1}{2}} - \Delta x q^{n}_{i}$
Repeat
    $p^{*}_{i+1/2} = p^{n+1}_{i+1/2}$
    $p^{*} = \frac{p^{n+1}_{i-1/2} + p^{*}_{i+1/2}}{2}$
    $\rho_r = \rho_r(p^{*}, T), \quad r = l, k$
    $V_r = (M^{n}_{r,i} + \Delta t f^{n+1}_{r,i-1/2})/\rho_r, \; r = l, k,$
    $v_{mix} = (V_l + V_k - A\,\Delta x)/\Delta t$
    $\alpha_r = V_r/(V_k + V_l), \quad r = l, k$
    $v_k = v_k(v_{mix}, \alpha_k), v_l = (v_{mix} - \alpha_k v_k)/\alpha_l$
    $f^{n+1}_{r,i+1/2} = \alpha_r v_r \rho_r A, \quad r = l, k$
    $M^{n+1}_{r,i} = M^{n}_{r,i} + \Delta t (f^{n+1}_{r,i-1/2} - f^{n+1}_{r,i+1/2}), \; r = l, k$
    $\Delta p_f = \Delta p_f(v_{mix}, \rho_k, \rho_l)$
    $q^{n+1}_{i} = \Delta p_f + g(\alpha_l \rho_l + \alpha_k \rho_k)\cos\theta$
    $p^{n+1}_{i+\frac{1}{2}} = p^{n+1}_{i-\frac{1}{2}} - \Delta x q^{n+1}_{i}$
Until $\left(\left|p^{*}_{i+1/2} - p^{n+1}_{i+1/2}\right| < tol\right)$
End do
```

Figure 12 – Predictor corrector algorithm (taken from **Paper I**).

In Fig. 12, $M^{n}_{r,i}$, $r = l, k$ are the masses present in the box i at time level n, N is the number of boxes, and the tolerance, *tol,* is a small numerical value which is used as criteria for defining when one is satisfied with the accuracy of the solution found by the iteration for each cell, Δt is the time step, Δx is the cell length. q represents friction gradient and hydrostatic pressure gradient.

5.2 Explicit AUSMV Scheme

The advection upstream splitting method hybrid scheme (AUSMV) is an explicit scheme where the conservative variables are updated in time based on variables from the previous time level. The well is discretized, and the conservative variables are defined in the center of each cell. The model includes acceleration terms that are associated with the generation of sonic waves. When the Drift-Flux model is used for well control evaluations, the effects of friction and acceleration are naturally included. A detailed description of the application of this scheme for the Drift-Flux model is, for instance, given in Evje and Fjelde (2002) and Udegbunam et al. (2015).

The Drift-Flux model can describe the transient behavior of a kick in e.g. a WBM system. In this case, one will have a system of nonlinear partial differential equations with two equations of mass conservation (one for each phase) and one combined conservation of momentum equation. These three equations can be expressed in a condensed form as (Eq. 25):

$$\frac{\partial}{\partial t}U + \frac{\partial}{\partial z}F(U) = Q(U) \tag{25}$$

where:

$$U = \begin{bmatrix} \alpha_l \rho_l \\ \alpha_g \rho_g \\ \alpha_l \rho_l v_l + \alpha_g \rho_g v_g \end{bmatrix},$$

$$F(U) = \begin{bmatrix} \alpha_l \rho_l v_l \\ \alpha_g \rho_g v_g \\ \alpha_l \rho_l v_l^2 + \alpha_g \rho_g v_g^2 + p \end{bmatrix}, \text{ and}$$

$$Q(U) = \begin{bmatrix} 0 \\ 0 \\ -q \end{bmatrix}.$$

This system of nonlinear partial differential equations was analyzed mathematically by Benzoni-Gavage (1993). It was shown to be hyperbolic describing propagation of a mass wave (e.g. a gas kick) and sonic waves that can propagate both upstream and downstream. Sonic waves are the product of flowrate changes or choke adjustments. The solution of the nonlinear hyperbolic system will involve propagation of sharp fronts or gradients. One example is the interface between a gas kick propagating and the drilling mud in front of it.

When a new time update (*n+1*) of the three conservative variables shown in Eq. 25 has been performed for all cells; one needs to combine these with additional closure laws to find the physical variables represented by pressure, phase densities, phase volume fractions, and phase velocities. The solution process for an explicit scheme is illustrated in Fig. 13 where each cell is updated. Eq. 26 illustrates this process.

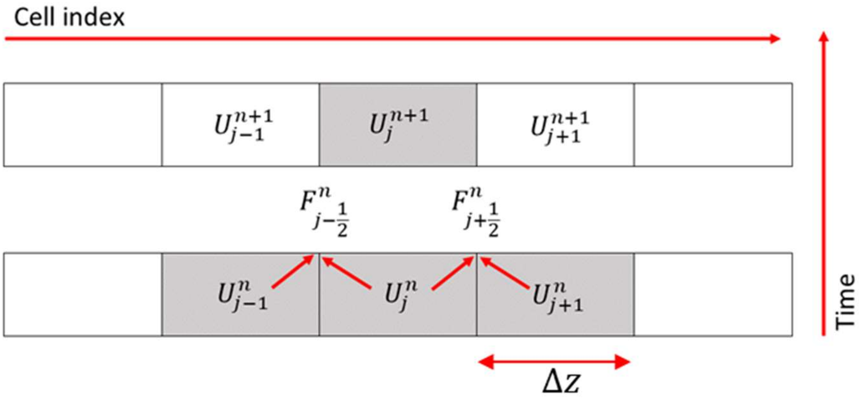


Figure 13 – Updating discretized variables using the AUSMV (Eq. 26).

$$U_j^{n+1} = U_j^n - \frac{\Delta t}{\Delta z}\left(F_{j+1/2}^n - F_{j-1/2}^n\right) + \Delta t \times Q_j^n \tag{26}$$

The formulas for the fluxes $F_{j\pm1/2}$ will depend on which explicit scheme is used. The flux formulas for the AUSMV scheme can be found in Udegbunam et al. (2015). The stability of an explicit scheme can be evaluated through the Courant Friedrichs-Lewy condition or CFL condition (LeVeque 1992). The Courant number indicates how the fastest wave is moving through the computational cells. The sonic waves propagate much faster than the mass wave (fluid particles). Hence, for explicit schemes there will be a strict time step restriction defined by Eq. 27. The Courant number (C) must be between 0 and 1. If the Courant number is less than one, the fastest wave can only move from one cell to another. However, if C is larger than one, the wave can cross several cells and this will lead to numerical instabilities when considering an explicit scheme.

$$\Delta t \leq \frac{C \times \Delta z}{u_{max}} \tag{27}$$

where u_{max} is the speed of the fastest sonic wave, Δt is the time step of the numerical model, and Δz is the spacing of the grid in the numerical model.

The boundary treatment will depend on factors such as whether the well is open or closed, and whether mud is being circulated or not. The fluxes at the inlet and the outlet have to be found by other means than using the AUSMV formulas. Examples of boundary condition treatment can be found in **Paper II**, **Paper V**, and Udegbunam et al. (2015).

The AUSMV is a first-order method. Fjelde et al. (2016) demonstrated that the effect of numerical diffusion when simulating kick migration can be quite substantial.

5.3 Techniques for Reducing Numerical Diffusion

Nonlinear hyperbolic systems describe propagation of sharp fronts that should be reproduced when using a numerical scheme. For instance, the interface between a two-phase flow region and a one-phase flow region should be tracked properly. However, numerical diffusion associated with the scheme will tend to smear out such discontinuities. In **Paper II, Paper III** and **Paper V** it was demonstrated that for a kick migrating in a well, numerical diffusion will tend to underestimate the maximum gas and liquid rates that can occur at surface. It will also overestimate how fast the kick will propagate and lead to premature prediction of gas breakthrough at surface. When a kick unloads a well, there will be a drop is bottomhole pressure. Numerical diffusion will also tend to underestimate how large this drop can be.

Numerical diffusion can be mitigated by increasing the number of cells at the expense of increased computational time. Another option is to employ the slope-limiter technique or front tracking to upgrade the accuracy order of a particular scheme.

In **Paper II**, a simulation case study varying the number of boxes and comparing a 1st vs. a 2nd order scheme is provided. The 1st order scheme was obtained with the AUSMV, and the 2nd order was obtained after upgrading the AUSMV with the slope-limiter technique. The pit gain time profile, shown in Fig. 14, shows the impact of numerical diffusion. Three simulations are shown using the second order scheme varying the grid refinement and comparing this with the first order scheme for a fixed discretization. Reducing numerical diffusion will lead to a higher maximum pit gain but the pit gain will also start to increase later. Both upgrading the scheme with slope-limiters and increasing number of boxes will help on restricting the numerical diffusion. The details of these methods are given in later sections.

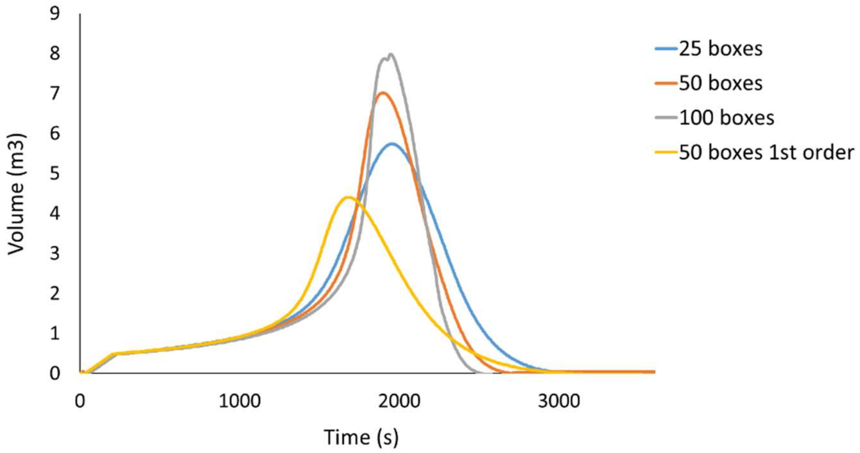


Figure 14 – Pit gain vs. time for different levels of numerical diffusion (**Paper II**)

5.3.1 Grid Refinement

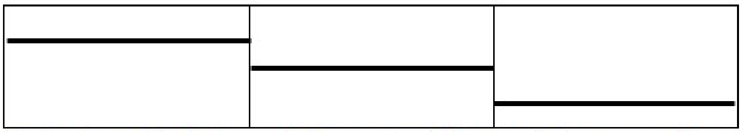
Paper II, Paper III and **Paper V** show that increasing the number of boxes, or cells, reduces numerical diffusion, increasing the accuracy of the solution. Both the front tracking technique and the slope-limiter approach are effective techniques for reducing the numerical diffusion, but only in combination with a sufficient number of grid cells in the computation.

The grid refinement increases computational time. If the number of boxes is increased further, the computational time will increase. 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 significantly. 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. The advantage of using slope-limiters or front tracking in combination with grid refinement is that it will be more computational efficient compared to using a first order scheme in combination with grid refinement. An accurate solution will be obtained using a rougher grid when using an upgraded scheme. This is discussed in **Paper II** and **Paper V**. At some point in the grid refinement process, the accuracy would not increase enough to justify a more refined grid.

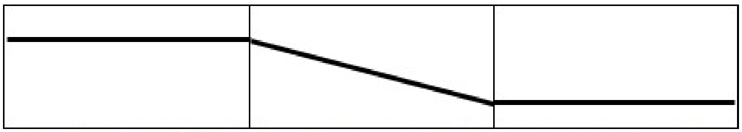
More technicalities about the discretization process and numerical schemes can be found in Hirsch (2007).

5.3.2 Slope-limiters

An effective strategy for upgrading first-order methods such as the AUSMV scheme into a higher resolution method is to apply the slope-limiter approach. According to LeVeque (1992) "*The basic idea here is to generalize Godunov's method by replacing the piecewise constant representation of the solution by* *some more accurate description, say piecewise linear*". In **Paper II**, **Paper V**, and **Paper VI**, the slope-limiter technique was used to upgrade the AUSMV into a second-order scheme. In this case, the physical variables are not considered constant within the cell. Instead, a slope is used to calculate the boundary values in each cell, which again are used for calculating the numerical fluxes. The minmod limiter is used (LeVeque, 1992). Figure 15 illustrates the concept. This approach is adopted for calculating densities, phase volume fractions, and pressure at the cell boundaries, which again are used for improved flux calculations. The slope-limiters in the boundary cells were copied from the nearest interior cell.



First order method: Flow variables are treated as constant across a cell.



Second order method/ Slope limiter concept: Gives better resolution of gas distribution in a well.

Figure 15 – Slope-limiter Concept (**Paper II**)

A good example of how numerical schemes can be improved with regards to numerical diffusion and accuracy by adopting slope-limiter techniques can be seen in Fjelde et al. (2003). Here, a Drift-Flux model was combined with a mechanistic two-phase flow model to simulate transient scenarios in underbalanced drilling. A WBM system was considered.

The slope-limiter technique was also applied to a semi-implicit method following a finite element approach and a predictor corrector shooting technique for solving multiphase flow problems by Lorentzen and Fjelde (2005). The numerical techniques were upgraded to higher-order accuracy using the slope-limiter approach. The methods were used to simulate two-phase flow in a vertical pipe. The results are compatible with second-order accuracy.

Practical simulation examples where the reduction of numerical diffusion in the AUSMV scheme has been addressed in Fjelde et al. (2016) and Ghauri et al. (2016).

5.3.3 Front Tracking

Another way to mitigate numerical diffusion is with the use of the front tracking technique. Front tracking exploits a fundamental approach to the numerical modeling of a fluid interface through the use of a numerically defined interface which plays an explicit role in the algorithm. A detailed explanation of this method can be found in Glimm et al. (1999) and Tryggvason et al. (2001).

The RF kick simulator presented in Ekrann and Rommetveit (1985), was based on the Drift-Flux model solved numerically by the predictor corrector shooting technique. Front tracking was employed to minimize numerical diffusion.

The front tracking technique is based on introducing a variable that tracks the interface between a two-phase flow region and a one-phase flow region. For instance, one can track the front of the kick since one can calculate the gas velocity and the time is known. This tracking imposes a limitation on when gas is allowed to flow from one cell to the next. First, when the gas front has reached the cell boundary, gas is allowed to flow to the next cell. This front tracking technique is also described in Rommetveit and Vefring (1991), where tracking of both the front and the tail of the kick was considered.

Fig. 16 illustrates the differences between front tracking and a first-order method where gas is assumed to be uniformly distributed across the cell. With the front tracking approach, two regions are considered in the cell: one with gas (dissolved or free) and one zone with only mud.

Figure 16 – Front Tracking technique (**Paper II**)

Front tracking is used both for the front and end of the kick (Rommetveit and Vefring, 1991). It can also be used to track the dissolved gas. The front tracking approach was used in the flow model presented in **Paper II**, **Paper III** and **Paper IV**. This flow model was provided by SINTEF Industry and it was based on using the predictor corrector shooting technique in combination with the Drift-Flux model. In **Paper III** it was seen that tracking of both dissolved gas and free gas is important to achieve accurate results.

6 Overview of the Research Papers

Paper I Probabilistic Flow Modelling Approach for Kick Tolerance Calculations

This paper describes a methodology for performing kick tolerance evaluations in a probabilistic manner where the uncertainty in the input parameters is considered. Kick tolerance is a quantitative evaluation of the kick sizes that can be circulated out of the well without having a situation where the pressure at the last set casing shoe exceeds the fracture pressure causing a possible underground blowout. The paper starts by discussing the parameters which affect the kick tolerances and the role of these calculations in casing design.

First, an analytical model was developed for predicting the maximum casing shoe pressure during a kick situation for static conditions (when kick is at bottom and well is closed). Insoluble gas in water based mud was considered. This model differs from a single bubble model in the sense that the gas volume fraction is an input parameter in the model making it possible to mimic a kick distributed in different ways. A simple transient flow model was also developed based on the Drift-Flux model and the predictor-corrector shooting technique. This was also used to simulate and explain the dynamics taking place during a conventional well kill using the Drillers method. A transient single bubble model was also developed and compared with the Drift-Flux model and the differences in the results are highlighted and shown to be substantial.

Both the analytical model and the transient flow model using the Drift-Flux model were then used in combination with the Monte Carlo method to show how it is possible to incorporate uncertainty in input parameters and propagate them through the simulations to obtain probabilistic output distribution of the maximum casing shoe pressure for comparison with the fracture pressure distribution. As a result, a probability for fracturing the formation at the casing shoe during kick circulation of a certain kick volume will be obtained. Emphasis was also put on showing how the probabilistic results could be presented to the engineer in different ways.

Although often neglected, there will always be uncertainty in input parameters used in the models. However, by adopting the probabilistic approach, it is possible to show the impact of the uncertainties on the results. When adopting this methodology, one also needs to define acceptance criteria for a design to be sufficiently safe.

Furthermore, it was demonstrated the applicability and purpose of sensitivity analysis when performing probabilistic calculations. It was also shown that some parameters will influence the results more significantly concerning uncertainty in the prediction, and thus, it is possible to identify which input parameters and model features are more significant for the probability of failure.

Both the use of the analytical model and the transient flow model using the Drift-Flux gave similar results for the simulation case considered. But, for more complex situations (e.g. gas kick dissolved in OBM), a transient flow modeling approach is preferable. It was therefore discussed how to optimize the calculation process in this case, the number of Monte Carlo simulations required and how to perform the simulation.

Paper II A Numerical Comparison and Uncertainty Analysis of Two Transient Models for Kick Management in a Backpressure MPD System

The motivation for this work is related to backpressure MPD systems and kick handling. Small kicks can be circulated to surface through the MPD equipment. However, the surface equipment must be able to handle the pressure and maximum flowrates occurring. Transient models can be used to evaluate the maximum flowrates that can occur. It is also important to consider the numerical errors in the prediction.

To analyze the effect of numerical diffusion, a simplified Drift-Flux model was considered, and a well test case was worked out. In the first simulation case, the AUSMV scheme with and without slope-limiters were applied. The effect of grid refinement was also demonstrated. It was shown that numerical diffusion has large impact on the results. By reducing numerical diffusion, higher maximum flow rates will be predicted and the time for kick arrival at surface will be delayed.

In the second simulation case, the AUSMV scheme with slope-limiters and the predictor corrector shooting technique with front tracking were compared to demonstrate and compare two techniques for reducing numerical diffusion. They produced similar results. Both techniques proved effective in reducing the amount of numerical diffusion assuming that a sufficient number of cells are used (probably more than 200). Hence, it is important that the engineers use a sufficient number of cells and are aware of the numerical diffusion. For a fixed number of cells, the slope-limiter technique seemed to keep the kick slightly more concentrated than the front tracking method. During the simulation work, it was also seen that it is important to smoothen the gas slip parameters properly in the transition from two-phase to one-phase gas flow to reduce numerical oscillations.

In the third simulation case, a more complete flow model based on Drift-Flux model and the predictor corrector shooting technique with front tracking was used to highlight the difference between a kick in OBM vs WBM for a backpressure MPD system. This model was provided by SINTEF Industry. One result was that the required backpressure was reduced when using an OBM system which could be an advantage considering the pressure limitations of surface equipment.

Paper III A Transient Flow Model for Investigating Parameters Affecting Kick Behavior in OBM for HPHT Wells and Backpressure MPD Systems

This paper presents a simulation study using the advanced flow model provided by SINTEF Industry. The motivation for the work is to study kick behavior using oil based mud in back pressure managed pressure drilling systems for subsea MPD systems. Here MPD equipment is placed on top of a riser and the evolution of this technology is described in the paper.

Small kicks in backpressure MPD systems are allowed to be circulated through the MPD equipment but one needs to evaluate the pressure limitation of the surface equipment (including riser) and the flow rate limitations for the mud gas separator. Hence, kick tolerances must also include this aspect and transient models can aid here.

The paper describes in more detail the typical behavior of gas influxes in OBM. At large pressures, kicks can become fully dissolved. However, when circulated toward surface, free gas will emerge. Two different PVT modelling approaches are briefly discussed (correlation vs compositional modelling).

The simulation model presented is based on the Drift-Flux model and the numerical solution method is based on the predictor corrector shooting technique with options to track both free gas and dissolved gas regions.

For the simulation study a case which mimics a backpressure MPD operation with riser using OBM was used. Here, the pressure conditions are such that kicks will be become fully dissolved when they are taken.

Two base cases were considered (Case 1 and Case 2). The main difference is that for the first case, the backpressure is not adjusted while in the second case the backpressure is adjusted to keep the bottom pressure fixed.

The first base case is used to simulate the dynamics taking place when circulating a kick without adjusting the backpressure. The pressure effect of the riser geometry is discussed but the main focus is discussing the dynamics related to appearance of free gas when the kick is circulated towards surface. This case is also used to perform simulations to study the impact of reducing numerical diffusion. Highest pit gain at surface (indirect measurement of the surface rates) are achieved for the most refined grid and it was also seen that front tracking on the dissolved gas was necessary to keep the kick concentrated without having numerical diffusion smearing it out.

The second base case is used to perform a sensitivity study on how different parameters will impact the system during kick circulation in a backpressure MPD system where the choke is adjusted to maintain the bottom pressure constant. First a simulation study is performed where the kick sizes are varied. Larger kicks will lead to higher maximum rates at surface but also a higher choke pressure and this must be checked against the limitations of the surface equipment. Maximum choke pressure will depend on both geometry effects (wider riser vs. narrower well) and the appearance of free gas when the kick starts boiling out. Larger kick size leads to an earlier increase in pit gain indicating that free gas appears at a deeper depth, introducing gas slippage earlier.

A simulation study is also performed where the target pressure at bottom is varied. When the target pressure is increased, the increase in pit gain is delayed since higher pressure in the well will shift the appearance of free gas to a shallower depth.

Then a simulation is performed where the effect of having a riser geometry is compared to having a uniform well geometry is shown. This will lead to differences regarding when the kick will arrive at surface, how choke pressure will evolve, and which pit gain and maximum rates can be expected at surface. For instance, the maximum gas rate was much less when having a wide riser, indicating that this could be beneficial with respect to the MGS limitation.

A simulation was also presented showing the maximum choke pressure for various kick sizes. The results obtained were not intuitive and could be worth further studies.

Finally, a simulation was presented comparing the use of a correlation model (Standing) with the use of a more realistic compositional model. The last model seems to provide a smoother transition from dissolved to free gas.

In summary, the paper shows the potential in using transient flow modelling to evaluate how different parameters will impact the results and how it is able to capture complex interactions that are not always obvious. It also demonstrates how the choice of closure laws and numerical approach for reducing numerical diffusion can impact the results and that the accuracy of the model must also be in focus.

Paper IV Transient Modelling and Sensitivity Analysis of Influxes in Backpressure MPD Systems

This paper represents a continuation of the work initiated in **Paper III**. The transient flow model developed by SINTEF Industry is used to perform a sensitivity study of kick behavior in OBM when using a subsea MPD system. The paper focuses on how different parameters affect the surface pressure and the maximum surface flow rates during circulation of kicks through the MPD system and how that relates to the limitations set by the MPD equipment.

In the simulation cases, a kick is taken under HPHT conditions and the kick will be fully dissolved in the mud in the beginning (bottom of the well). Free gas will emerge when the kick is circulated upwards.

In case 1, a kick is circulated up subjected to different backpressures. It is shown that increased backpressure will shift the bubble point upwards and limit the amount of free gas being released. The appearance of free gas will also be delayed. It is also demonstrated that small increase in choke pressure can lead to significant changes in the bottomhole pressure due to solubility issues.

In case 2, the bottomhole pressure is kept constant and various kick sizes are circulated to study the impact on pit gain, choke pressure and surface flow rates. Larger kicks will tend to induce free gas deeper in the well and kicks will emerge at surface earlier and both surface flowrates and choke pressure will be larger. It was seen that quite large kicks can be handled without threatening the integrity of the surface equipment when using OBM. In this aspect, it might be advantageous using OBM instead of WBM.

In case 3, the impact of various riser geometries was compared when circulating kicks with a fixed bottomhole pressure. A wider riser will lead to a reduction in maximum gas rates and a reduction in choke pressure when the kick arrives at surface. This confirms the results also seen in **Paper III**.

In case 4, the effect of changing the circulation rate during kick circulation is demonstrated. The reduction in the flow rate will lead to a decrease in the maximum flow rates observed at surface. This reduce the risk of exceeding the MGS limitations. However, an increase in choke pressure will also be seen since reduced well friction must be compensated.

This paper demonstrates that transient models in combination with sensitivity analysis can be a valuable tool for obtaining more insight into the dynamics of a kick in a backpressure MPD system and how different parameters will impact the surface pressures and maximum surface flow rates during kick circulations.

Paper V Numerical Modelling and Sensitivity Analysis of Gas Kick Migration and Unloading of Riser

The paper describes a transient model based on the Drift-Flux model solved using the AUSMV scheme with the application of the slope-limiter technique to restrict numerical diffusion. A simulation study of riser unloading in non-Newtonian water based muds was carried out. In such fluids, small gas volumes can be trapped (suspended) in the mud and not reach surface. The Drift Flux model was supplemented with a gas slip relation that accounted for having different flow patterns in the riser, i.e. suspended gas, bubble flow, slug flow and a smooth transition to one-phase gas flow. This numerical model had not been used for riser unloading analysis before and special focus was on studying the effect of gas suspension and the effect of numerical diffusion. The model adopted have proven useful for understanding the dynamics of gas kicks in risers and also to get insights on possible mitigation actions.

Four cases were simulated with the objective of studying various riser unloading scenarios. A 3000-meter-deep riser was considered and kicks were introduced at the bottom of the riser. It is studied how certain parameters such as numerical diffusion, suspension limit, kick sizes and circulation conditions will impact the unloading scenario.

In case 1, the impact of grid refinement on the results is studied. A kick is introduced at the bottom the riser and circulated upwards. The grid refinement is related to reduction in the numerical diffusion. It was observed that reducing numerical diffusion tends to provide sharper curves and higher peaks for pit gain, liquid rate, and gas rate at surface. Reducing numerical diffusion also cause a larger BOP pressure drop. It is also observed that as we keep increasing the grid, the difference in the results will be less significant. Since increasing the grid refinement results in more time-consuming simulations, it is smart to find the optimum grid refinement that will provide reasonable accuracy within a reasonable computational time. In this case, 200 cells seemed to be sufficient to reduce the numerical diffusion to an acceptable level.

In case 2, the suspension limit is varied. The pumps are off and the gas kick is injected in the bottom of the riser and migrates on its own. For a zero suspension limit, we will have a maximum unloading scenario where all gas moves upwards and unloads the well. When we adopt a suspension limit of 3% the kick gets fully suspended along the riser, before being able to reach the surface. In this case, no unloading will occur. We also presented simulations for different suspension limits in between zero and 3 %. The results also show, for each suspension limit, what is the final mud level in the well after the unloading (if any). The suspension limit will also impact the time that it will take for the kick to reach the surface. The model is also used to show depth profiles at a certain time to visualize how the gas is distributed along the riser.

The kick size is varied in case 3. Here the suspension limit was fixed to 3 %. Pumps are off and again the gas migrates to the surface. Sensitivity analysis in terms of kick size allows one to understand above which kick size the operation is at risk. Larger kicks will translate into higher liquid and gas rates observed at surface. Larger sizes will increase the risk of severe riser unloading. In the paper, there is a table summarizing the results for different combinations of suspension limits and kick size. It shows for which combinations that one can expect the riser to unload or that the kick becomes fully trapped.

In case 4, a kick is injected in the bottom of the riser with pumps off. The kick becomes fully suspended and only after that circulations starts. We circulated the suspended kick at different rates, and it is shown that lower circulation rates lead to reduced liquid and gas rates at surface. Also, the suspended kick takes more time to be removed from the riser. Huge among of fluids arriving at surface can be challenging. When we compare case1 (circulation from the beginning) and case 4 (pumps are turned on after the kick got suspended), it is clear that for the same conditions (kick size, type of mud, suspension, well geometry, etc.), it is clear that it can be advantageous to wait for the kick to become fully suspended before starting circulation – at low rates.

Paper VI Gas Suspension Effects in Riser Unloading and Appropriate Modelling Approaches

In this paper, riser unloading in water based mud was simulated using two different models: one based on the single bubble approach and the other based on the Drift-Flux model, each one solved by different methods.

The Drift-Flux model is fundamentally different from the single bubble approach since it takes into account that the gas can be dispersed in the drilling fluid (two phases can exist at a location simultaneously). It also has to be supplemented with a gas slip relation which takes into account that gas moves faster than the drilling fluid. The Drift-Flux model implemented here takes into account that different multiphase flow patterns will occur and we have included four regimes i.e. suspended gas (no slip), bubble flow, slug flow and a transition to one-phase gas flow (no slip). What flow pattern that will occur in a certain location in the well/riser depend on the gas volume fraction in the corresponding cell and the flow regime will determine what gas slip relation shall be used. The Drift-Flux model is solved by the AUSMV scheme using slope limiters to reduce numerical diffusion similar to what was done in **Paper V**.

We first compared our transient Drift-Flux model with two transient single bubble models. The first single bubble model is solved numerically using the bisection method and the second single bubble model is solved analytically. The single bubble modelling approach is well known for providing conservative results. It assumes that the gas occupies the whole cross-sectional area and moves as a separate unit in the well/riser with drilling fluid below and above. It does not account for gas slippage.

The Drift-Flux model was then used further to explore how the gas suspension effect impacts key parameters such as the pressure at BOP, pit gain, surface rates, friction in riser and gas distribution inside the riser during a riser unloading scenario.

The Drift-Flux model was also used to perform a sensitivity analysis varying riser length, riser diameter, kick size and suspension limit to study the impact on the unloading scenario. It is shown that a transient model can capture the kick dynamics in different scenarios and can determine whether a certain kick will become suspended or if it will unload the riser.

In case 1, we simulate a gas-in-riser event using the two single bubble models and the transient Drift-Flux model. Here, we do not consider suspension (set to zero) and the riser does not stay unloaded because the circulation is continuous. The single bubble modelling approach proves to be more conservative because it predicts higher surface rates and more significant impact on the BOP pressure. It also overpredicts how long time it will take for the kick to unload the riser. A comparison between the two single bubble models using the kick height development vs. time shows a good match.

In case 2, it is demonstrated that changing the suspension limit in the transient Drift-Flux model will impact the results. In this case, there is no circulation and as the suspension limit is decreased, it is possible to see that the unloading is more severe in terms of surface rates. Lack of capability of keeping gas in suspension will also lead to higher friction, lower final mud level and lower hydrostatic pressure in the riser. The observations suggest that the unloading is potentially more dangerous for the no suspension case, since it can be harder to handle so much mud arriving at the rig surface. On the other hand, for the highest suspension limit tested (3 %), a 4 m^3 kick didn't reach the surface when considering a 2000-meter riser, meaning that the kick became fully suspended along the riser. This situation can be easier to manage as the kick can be removed from the riser at low circulation rates without severe changes in the surface rates and pressures.

Case 3 focused on sensitivity analysis. The effect of varying riser length, kick size, riser inner diameter, and suspension limit were studied. The different simulated scenarios were also concentrated and summarized in different tables which show in a practical way for which scenarios an unloading event is more likely to occur. The most potentially dangerous situation in terms of unloading severity is the case with smaller suspension limit, larger kick, shorter riser, and smaller riser ID.

Overall, it is demonstrated that a transient Drift-Flux modeling approach can be applied for estimating whether an unloading event will take place after gas enters the riser or if kicks of specific sizes will likely become suspended without reaching the surface. Single bubble models cannot be used for this purpose. This kind of analysis are useful for well planning, risk analysis and optimization.

7 Conclusion and Future Work

7.1 Conclusion

This Ph.D. project explored the utility and ways of improving transient flow models for well control situations. It was demonstrated how such tools can be used for:

- Kick tolerance calculations in combination with Monte Carlo simulations for obtaining probabilistic outputs (traditional wells);
- Kick tolerance calculations for MPD systems focusing on estimating surface flow rates and surface pressure in relation to surface equipment limitations;
- Studying the kick behavior in OBM vs. WBM;
- Predicting if a kick will become fully suspended or if it will migrate upwards and unload the riser, in an open well configuration, filled with WBM – when considering gas suspension effects;
- Investigating ways of handling a kick in different scenarios;
- Performing sensitivity analysis of key parameters such as pore pressure, kick volume, discretization, PVT model used, riser geometry, suspension limit, mud pump rate, choke pressure, among others.

The proposed approach of using different models for evaluating maximum casing shoe pressure at the shoe during a kick scenario in combination with Monte Carlo simulations for kick tolerance evaluations is, to our knowledge, new. This approach makes it possible to quantify the probability of losses at the weakest spot in the formation (considered at the shoe depth) for a specific kick volume.

An analytical model was developed assuming that the free gas kick was at bottom when maximum casing shoe pressure was achieved, and it was here possible to specify the uncertainty in the initial distribution of the kick. It was demonstrated that this approach is useful for evaluating the probability of a specific kick volume leading to losses at the weakest spot in the formation during a well kill and it was shown that sensitivity analysis is useful for identifying which parameters affect the kick tolerance most. It was also demonstrated that a fully transient Drift-Flux model has the advantage of being more accurate since it can handle both initial distribution of kick, gas slippage, gas expansion, and it can also take into account solubility issues when an oil based mud is used. If the proposed methodology shall be taken into use, one needs to work out acceptance criteria for when a certain kick size can be circulated safely to surface.

Kick handling was studied in different scenarios by using different transient mathematical models (single bubble and Drift-Flux) and different numerical schemes (predictor-corrector shooting technique and AUSMV scheme). The results published provide elements for important discussions considering the dangerous situations that might evolve from a kick. As demonstrated in the publications produced during this Ph.D., the handling will depend on the drilling mud.

When using OBM, gas kicks can become fully dissolved and free gas will first emerge in the well when the kick is circulated towards the surface followed by a rapid increase in pit gain. Only a transient model is capable of simulating such scenario. A transient Drift-Flux model, if equipped with a proper PVT model, can also be used to model when the system will reach the dense phase, i.e., the conditions where infinite amounts of gas can be dissolved in the oil based mud.

It is important to be able to predict at which depth in the well free gas will emerge during kick circulation. This will again influence the rates seen at surface, when the gas kick reaches the surface and how the choke pressure has to be increased to maintain bottomhole pressure constant.

The simulations have shown that emergence of free gas depends on different factors such as kick size and required choke pressure to maintain target pressure at bottom. In addition, the choice of PVT model will also have an impact on how the phase transfer from dissolved gas to free gas takes place. In addition, it was demonstrated that it is important to reduce numerical diffusion so that the dissolved gas does not get artificially spread out in the well.

When using WBM, the rates observed at surface will, in general, be higher compared to similar kick conditions using an oil based mud. A larger choke pressure is also required to maintain the bottomhole pressure constant. Here the gas will always be in free form and there will be gas slippage from the beginning, when the kick is taken.

The handling of the kick will be different if one is using a backpressure MPD system instead of an open well configuration. Small kick sizes can be circulated through the MPD surface equipment if they do not pose a threat to the surface equipment limitations.

The simulations show how one should manipulate parameters such as choke pressure and flow rate to handle the kick in a safe manner. This involves considering the surface equipment limitations, especially for MPD, in terms of pressure and volume capacity. In this perspective, it is advantageous to reduce the maximum flow rates that will occur at surface and one recommendation based on the simulation results is to use reduced mud pump rate while circulating the kick out through the MPD equipment. It was also interesting to observe that for oil based mud, it seems that the MPD system can handle larger kick sizes compared to when using water based mud due to the solubility of gas in oil based mud. It was also demonstrated that the presence of a riser in the MPD system will have an impact on the simulated results. First, there is an effect of geometry when a kick leaves the rather narrow well and enters the wide riser. In addition, a wide riser will reduce the maximum gas rates seen at surface and it will also lead to a reduced choke pressure when the kick arrives at surface compared to what would be the result if a narrower geometry would be considered (casing to surface).

Gas kicks entering the riser in conventional drilling can potentially unload the riser with severe consequences. It has been shown how the Drift-Flux model solved by the AUSMV scheme can be used to study how the gas suspension limit will affect the severity of the unloading scenario, considering an open riser filled with WBM. Although the suspension limit is often neglected in the flow models, it has been shown in this research that this effect is significant and should not be neglected. The simulations show that smaller suspension limits lead to more severe unloading events. Higher suspension limits mean that the system is capable of keeping more gas in suspension. Depending on the kick size, the riser capacity, and chosen suspension limit, the gas might become fully trapped along the riser and might not reach the surface if not circulated out. It can potentially be an idea to work out tables showing for which conditions a riser will be unloaded or not as demonstrated in the papers.

When considering WBM and gas in riser events, it has been demonstrated by the simulations that it is advantageous to let the gas become suspended in the riser before attempting to circulate it out because it helps to decrease the maximum rates at surface when the kick is removed. This confirmed earlier observations.

In this work, the single bubble model and the Drift-Flux model have been compared for kick scenarios in water based mud considering both kick circulation and riser unloading. The single bubble model provides more conservative results. During a well kill, it predicts higher pressure both at the casing shoe and the choke compared to the Drift-Flux model. For a riser unloading scenario, it predicts larger pit volume and larger drop in the bottomhole pressures expressing that more drilling fluid is expelled compared to what would be seen using the Drift-Flux model. One can also note that the predicted time for the kick to reach surface will be overestimated when using the single bubble model since gas slippage is not considered. For realistic kick evaluations, it is recommended to use the Drift-Flux approach since it includes gas distribution in the mud and it can incorporate gas slippage, which again will depend on the flow patterns that can occur.

Numerical schemes can be prone to numerical diffusion and it was demonstrated that the numerical errors can be quite significant. It is crucial to use tools for restricting the numerical diffusion for predicting the maximum rates at surface when a kick arrives at the MPD surface equipment or when a kick unloads a riser.

To reduce the numerical diffusion, one should first attempt to use different techniques such as the slope-limiter or front tracking. This must be combined with a sufficient grid refinement. In this work, both front tracking and slope-limiter techniques were used for predicting maximum rates at surface and compared directly. They showed similar results and both represent two effective strategies for reducing the numerical diffusion when combined with a sufficient grid refinement. For the MPD case considered, 200 cells have proven to be needed. When using the front tracking method, one must ensure that both free and dissolved gas are tracked.

Another interesting observation was the impact of how to determine the parameters used in the gas slip relation (K and S). For unloading scenarios, in some situations the gas volume fraction will approach 1 and there is a need to consider the interpolation of the K and S parameters from a typical slug flow values to one phase gas flow values (K=1 and S=0). Different interpolation approaches were adopted and the results show that using a broader interpolation interval yield more stable results, with less oscillations.

This research has demonstrated the importance of selecting carefully the models, the closure laws, and numerical schemes, given the difference observed in the results. It has also been demonstrated that it is important to be aware of and reduce numerical diffusion especially to evaluate maximum rates predicted at surface for the scenarios considered. It has also been demonstrated that the use of sensitivity analysis in combination with transient modelling can be used to map how different parameters will influence the simulation results.

7.2 Future Work

There are interesting opportunities for extending our models and improving the accuracy of the results. One of the interesting opportunities for moving forward is extending the Drift-Flux solved by the AUSMV scheme to work with OBM besides WBM.

This research has also shown the importance of considering the gas suspension effect in WBM. More work should probably be invested in developing correlations for how the suspension limit will vary for various conditions although some work has been reported on this earlier (Nes et al. 1998).

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