Consequence Analysis of Uncontrolled Fluid Flow in Wellbore

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Introduction

Uncontrolled fluid flow in the wellbore is one of the most critical safety concerns for the oil and gas industry. It can result from petroleum seepage, gas-kicks, and blowouts. Petroleum seepage takes place when the seal above the reservoir has been breached. In a variety of operational phases, if the wellbore pressure provided by drilling mud is less than the formation pressure, the formation fluid will flow into wells from the reservoir. This is known as kicks, and is described in many references (Bourgoyne 1991). The rate of fluid influx is a function of reservoir parameters and the pressure difference between the formation and wellbore. There are several indicators of kicks, including (Grace 2003):

- Sudden change in drilling rate
- Increase in flow rate
- Change in pump pressure
- Reduction in drillpipe weight
- Gas, oil, or water-cut mud

After detecting a kick, proper well control procedures must be performed immediately to eliminate the fluid influx and prevent further formation fluid from flowing into the well. The wellbore must be isolated from the surface by activating blowout preventers (BOP). Then the remaining fluid influx is circulated out to the surface. Once the influx has been displaced, heavier drilling mud is pumped into the well in order to regain control of the well. However, as can be seen from the incident history of the oil and gas industry, such procedures do not always succeed. If the kick is out of control, it may lead to a blowout.

A blowout is defined as the uncontrolled release of formation fluid including crude oil and/or natural gas from the formation to the outside surroundings after the wellbore control measures have failed. Although the drilling and production well planning may be good, the measurement and detection systems used are sophisticated and accurate, and personnel receive comprehensive training, blowout events can still occur and lead to severe consequences, such as the deepwater Macondo incident in the US Gulf of Mexico (GOM). These consequences include:

- Fatalities and injuries of personnel
- Environmental impacts
- Reservoir depletion
- Loss of production
- Risk associated with the flow of formation fluids (flammable, explosive and toxic)
- Loss of equipment
- Blowout control cost
- Loss of company credibility

Despite of the proper emergency response plans, some blowout events can last for a significantly long time, such as more than one month. For these blowouts, the production loss and corresponding environmental impact are not straightforward to be evaluated.

In the past, the crude oil spill and natural gas leakage due to the blowouts have damaged the environments in Alaska, the Gulf of Mexico, and many other places. For example, the Gulf War oil spill in 1991 is known as one of the largest oil spills in history. When Iraqi forces invaded Kuwait, they set over 600 oil wells on fire in January 1991 to achieve their strategic goal—prevent potential landings by US Marines. The fire lasted for about ten months. Until November 6, 1991, all blown-out oil wells due to the Gulf War were officially shut down (Grace 2003). There were 11 fatalities associated with the Kuwait fires by that time (Grace 2003). The oil spill left over 200 oil lakes throughout the desert, and some of them were more than six feet deep. The cleanup work is continuing until today.

Different parties conducted research to estimate the volume of oil spilled during the Gulf War. Initially, media estimated the spilled amount could reach about 1.7 million cubic meters at the beginning of the Gulf War oil spill (Landrey 1991). After all the wells were shut in, the US Committee on Merchant Marine and Fisheries reported to Congress that the volume of the oil spill ranged between 640 to 960 thousand cubic meters (Congress report 1992). The methods adopted in the above two estimations are not clear. In 1993, Khordagui and Al-Ajmi (Khordagui 1993) reported that the maximum amount of spilled oil should be around 320 to 640 thousand cubic meters based on the historical and incident data.

It can be concluded that these three estimations did not agree with each other. The obvious drawbacks of the above estimates include a lack of basic physics to understand the behavior of blowouts; therefore, their estimates are not accurate. Unfortunately, very few papers have addressed the production loss and environmental impact during blowouts which are directly related to the blowout rates. Clark and Perkins (Clark 1981) are perhaps the first researchers who tried to understand the blowout mechanism. They presented a pioneering work to calculate the critical flow velocity, pressure, and temperature at the exit of an oil well blow-out. Hasan *et al.* (Hasan 2000) also investigated the wellbore dynamics during an oil well blowout. In 1996, a method for blowout rate prediction for sour gas wells was studied by Kikani *et al.* (Kikani 1996). Oudeman and his colleagues (Oudeman 1993, Oudeman 1998, Oudeman 2006, and Oudeman 2010) accomplished a series of work focusing on simulating blowouts based on observations, such as wellhead pressure and temperature, plume shape and size, noise field around the wellhead, the pressure response of nearby wells, and production data of the wells with high flow rates, to develop proper well control strategies. Blowout events are dependent on not only the wellbore configurations, but also the reservoir conditions. In addition, their interaction must be taken into consideration. However, none of the above outstanding works covered all these important components, and the blowout mechanism is still not fully understood.

Methodology

In this paper, a comprehensive simulation of blowout behaviors is performed. To maintain the completeness of the model, the transition period and pseudo steady state period are addressed by this blowout model. The transition period occurs during early time of the reservoir. Given the large radius of a reservoir, the pressure response generated by the wellbore fluid may not be detected at somewhere far away from the well, such as the boundaries. Within time progressing, such response travels further and further until it becomes detectable to the boundaries of the reservoir. It is known as pseudo steady state. The time span is divided into a number of time steps to keep the accuracy. When the blowout begins, the blowout rate depends on two main factors—pressure difference between discharging pressure (p_1) and outside pressure (p_2) around the wellhead, and reservoir pressure. When the pressure ratio at the wellhead is larger than the ratio obtained by the following equation (Smith 2005):

$$\frac{p_2}{p_1} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma+1)} \quad (1)$$

where γ is the heat capacity ratio of wellbore fluid, it will result in sonic velocity at the wellhead. For single phase oil wells, in most cases, sonic velocity is not attained. However, this phenomenon is particularly true for single phase gas wells and two-phase flow wells. The sonic velocity of gas is derived from thermodynamic knowledge by assuming an ideal gas:

$$c = \left(\gamma \frac{R}{M} T\right)^{0.5} \quad (2)$$

where M is the molecular weight of the gas. For natural gas, it is assumed to contain 94% methane and 6% ethane. Based on Equation (2), the sonic velocity of natural gas is 431.3 m/s under standard conditions. The sonic velocity of liquid can also be derived as:

$$c = \left(\frac{E}{\rho}\right)^{0.5} \quad (3)$$

where E is bulk modulus elasticity of liquid, defined as:

$$E = -\frac{dp}{dV/V} \quad (4)$$

The sonic velocity of crude oil depends on its physical properties. For liquid/gas mixtures, Wallis (Wallis 1960) proposed the following expression:

$$\frac{1}{c^2} = [f_L \rho_L + (1-f_L)\rho_g]\left(\frac{f_L}{\rho_l c_L^2} + \frac{1-f_L}{\rho_g c_g^2}\right) \quad (5)$$

From preliminary experiences, the blowout rate of onshore gas wells and two-phase flow wells always reaches sonic velocity. For offshore wells, as the hydrostatic pressure is high, the pressure difference between the discharge pressure and hydrostatic pressure is not large enough to support a sonic flow rate. In general, if the sonic velocity can be attained at the wellhead, the blowout behavior is governed by sonic velocity until the reservoir pressure cannot support such velocity due to the depletion. Then the blowout is dependent on the reservoir pressure. If the sonic velocity cannot be attained, the blowout rate will only depend on the reservoir pressure.

At the initial time step, we first assume that sonic velocity can exist. Thus we can use sonic velocity of the fluid as an initial guess assuming a fluid temperature at the wellhead. Because the bottomhole pressure is a function of reservoir pressure and blowout rate, it can be calculated by the input of the initial guess of blowout rate and reservoir pressure. A bottom-to-top calculation is performed in the wellbore portion to calculate the wellhead pressure. If the calculated wellhead pressure is higher than ambient pressure constraints (atmosphere pressure for onshore and hydrostatic pressure for offshore), the sonic velocity exists under such conditions. In addition, the fluid temperature at the wellhead is solved based on the initial guess of the blowout rate. So a better guess of sonic velocity under the calculated wellhead temperature is needed until it reaches convergence by an iterative solution procedure. Then we proceed to the next time step to calculate the production loss and corresponding reservoir pressure during this time step. We continue iterating with further time steps until the calculated wellhead pressure is not larger than the ambient pressure constraints. It indicates that the blowout behavior changes to a reservoir pressure governed mode. In this mode, a different algorithm is needed. Due to the constraints of ambient pressure, the wellhead pressure is fixed in the reservoir pressure governed mode. We guess a blowout rate as the starting point. Based on the reservoir pressure from the material balance, the bottomhole pressure is calculated. A bottom-to-top calculation is performed to obtain the wellhead pressure. If the calculated wellhead pressure is equal to ambient pressure, we can proceed to the next time step. Otherwise, a better guess of blowout rate is needed by a trial-and-error method. If the calculated wellhead pressure in the first time step is less than ambient pressure, it means the reservoir cannot support such a large velocity. Therefore, the blowout behaviors are only governed by reservoir pressure. The algorithm is similar to the reservoir pressure governed mode discussed in this section.

Case Study

The Macondo well was located in the Mississippi Canyon Block 252 of the US GOM, 209 kilometers away from New Orleans. It was a 10,683 meters deep exploratory well in about 1,554 meters of water. In April 20, 2010, the explosion of the Deepwater Horizon drilling platform led to a blowout of the Macondo well for 87 days, killing 11 operators. The blowout was finally capped on July 15, 2010. It is considered as one of the largest accidental marine oil spill in the history of oil and gas industry. The incident severely damaged the underwater equipment including the riser. During the incident, there were two main leak points. The main leak came from the broken end of the riser until the severing operations, which was far away from blowout preventer (BOP). After May 1, 2010, a second leak source appeared in the kinked riser above the BOP. A number of strategies to stop the flow of oil were proposed. Since it is difficult to access to the well, and the prevention operations needed to be performed at the seafloor where the temperature is low and the pressure is high, none of these strategies successfully capped the uncontrolled release. The public started to pay attention to the accurate estimation of the magnitude of the oil and gas discharged into the environment. This information is important for evaluating the environmental consequences of oil and gas release, developing proper control strategies and evaluating the liability of the operating companies for the environmental damage.

The oil spilled caused by the Macondo incident was only collected up to 25,000 barrels per day by surface ships during the latter portion of the incident. The actual release observed from the bottom of the sea by camera was higher than the collection rate. Therefore, the estimation of the volume of oil discharged cannot be determined solely by the collection data. In this section, the blowout model in this work is used to quickly generate an estimation of the flow rate and volume of oil spilled from the Macondo well. The configuration of the Macondo well and properties of the reservoir is given in the following table.

Table 1. Macondo well configurations and reservoir properties (Plume Calculation Team 2010, Interagency Soluction Group and Flow Rate Technical Group 2011, and Oldenburg 2011)

Property	Value
Sea floor properties	
Temperature at the sea floor	278 K
Depth to the sea floor	1,544 m
Pressure at the sea floor	15,451 kPa
Well properties	
Length of 9 7⁄8 in casing	2,347 m
ID of 9 7⁄8 in casing	0.218 m
Length of 7 ½ in casing	1,676 m
ID of 7 ½ in casing	0.155 m
Reservoir properties	
Depth below sea floor	4,054 m
Thickness	29.1 m
Porosity	21.70%
Permeability	223.7 md
Water saturation	12.60%
Reservoir radius	1,390 m
Pressure	81744 kPa
Temperature	349 K
Fluid properties	
Oil gravity	0.85
Gas-oil ratio	1600 scf/bbl
Gas gravity	0.74

It is assumed that the two main leak points can be approximated to one leak source that was above the BOP throughout the blowout. The pressure exerted by the sea water at the sea floor was about 15,513 kPa. This pressure was exerted at every leak point where fluid can flow out of the well. Therefore, the wellhead pressure in this model is set to 15,513 kPa. The simulation results are shown in Figure 1. Due to the high permeability given by the literature, the initial blowout rate is relatively high. The reservoir depleted fast during the blowout owing to the high flow rate, therefore the reservoir pressure declined fast as time progressed. At the end of the blowout, the rate decreased to around 10,000 STB/D and the oil discharged into the sea reached nearly six million barrels. The average blowout rate during the Macondo incident was 65,630 STB/D.

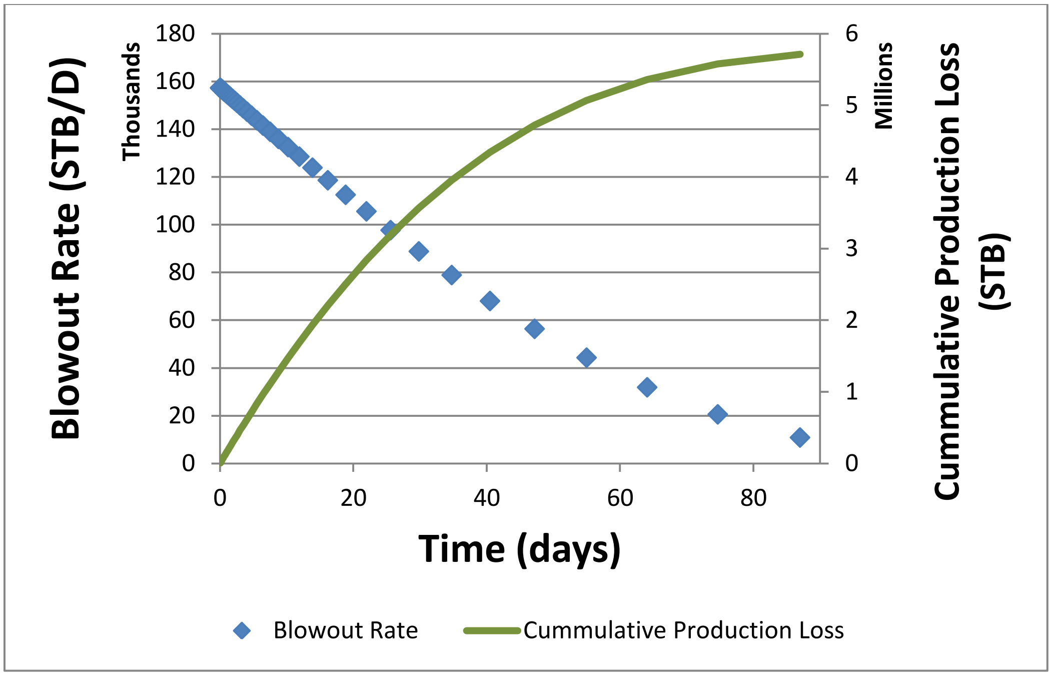

Figure 1. Simulated blowout rate and cumulative production loss during Macondo incident

Some research has been conducted to estimate the blowout rate during Macondo incident, shown in Table 2. Due to the various methods adopted by different research parties, the estimation of the blowout varies significantly. Moreover, although most of researchers mentioned that the blowout rate should vary within time, they cannot give an accurate estimation on the blowout rate as a function of time because of the limit of data that was used in their work. However, we still could conclude that our estimation of blowout rate during the Macondo incident is comparable with the results obtained by different methods.

One potential issue with the data given in Table 1 is that the permeability is higher than the typical value in the US GOM based on our field experiences. The measurement of permeability in the field relies on well testing, which usually occurs after the completion of a well. For the Macondo well, since the blowout happened during the drilling phase, the knowledge to the permeability may not be accurate. Figure 2 shows the sensitivity analysis given different values of permeability. The initial blowout rate highly depends on the reservoir permeability. High permeability results in high initial blowout rate. The blowout rate at high permeability declines faster than it does for low permeability owing to the quick depletion of the reservoir.

Table 2. Estimations of blowout rate during the Macondo incident by current research

Estimation techniques	**Estimation of blowout rate (STB/D)**
Using probability distributions to model the uncertainty implied in experts' assessment (Plume Calculation Team 2010)	46,000
Analysis of videos of discharging flow (Plume Calculation Team 2010)	45,000
Analysis of videos of discharging flow (Plume Calculation Team 2010)	30,000 to 40,000
Analysis of videos of discharging flow (Plume Calculation Team 2010)	68000
Measuring oil jet velocities using manual Feature Tracking Velocimetry (Plume Calculation Team 2010)	61,000 ± 15,000
Analyzing the velocity profile and trajectory profile of oil leak jets using established theory of turbulent jets (Plume Calculation Team 2010)	89,000 with a range of 62,000 to 116,000
Simulating the trajectory of a buoyant oil leak jet using computational fluid dynamics (Plume Calculation Team 2010)	55,000 to 70,200
Acoustics analysis(Interagency Solction Group and Flow Rate Technical Group 2011)	60,000
Reservoir modeling from 3-D seismic data (Interagency Solction Group and Flow Rate Technical Group 2011)	27,000 to 102,000
Well modeling (Interagency Solction Group and Flow Rate Technical Group 2011)	30,000 to 118,000

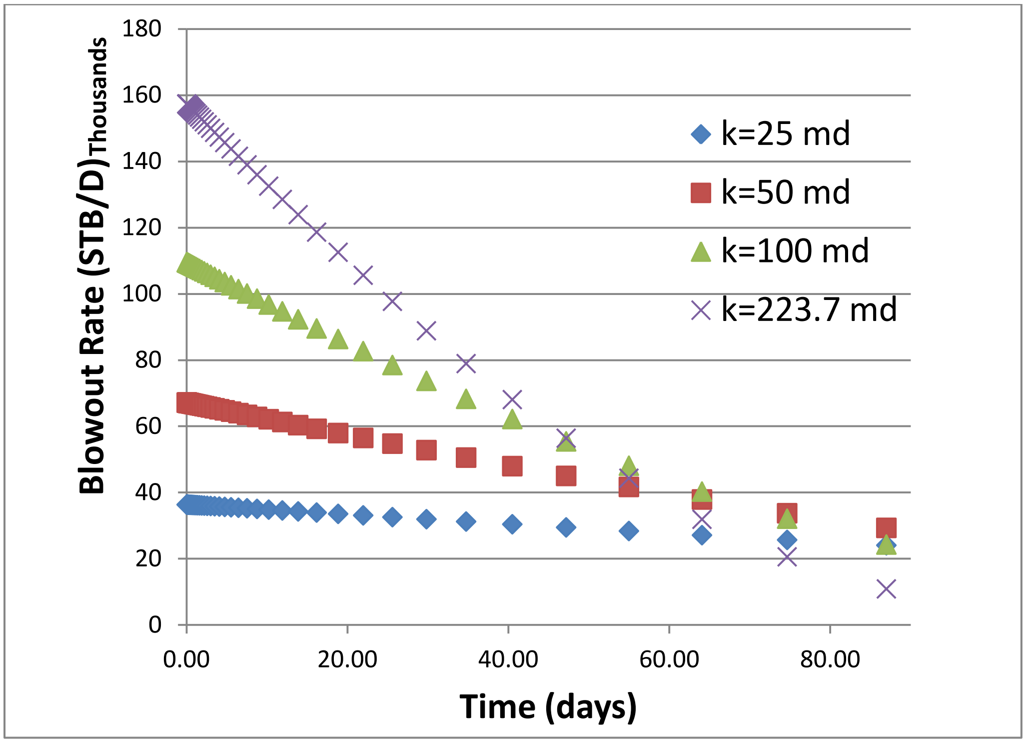

Figure 2. Blowout rate evolution with different permeability

The measurement of permeability and other parameters of the well and reservoir determined during well testing could lead to significant differences with respect to the oil spill volume. In the case of the Macondo incident, we consider the uncertainties of these variables, including reservoir pressure, reservoir radius, formation thickness, and skin. Reservoir radius and formation thickness represent the volume of the reservoir, which relates to initial oil in place. Skin is a numerical value describing the condition of the well. Zero skin represents the ideal case that the pressure drop matches the value predicted by Darcy's law. However, the damage or the stimulation to the well lead to the deviation between the real and predicted pressure drop. Negative skin indicates the well is under stimulation, and positive skin means the well is damaged. During drilling operations, the drilling mud extrudes into the rock, and therefore damages the well. So skin is considered as one of the important variable in our model.

Table 3 presents the matrix used in a three-level, Plackett–Burman design. In this table, p-10, p-50 and p-90 represent the probability of occurrence of each variable. In this design, nonlinearities are captured, such as interactions between independent variables. Solutions of cumulative production loss are generated by the blowout simulator in this work.

Table 3. Uncertainties of selected variables, Plackett–Burman design

Variables	p-10	p-50	p-90
Permeability, md	25	100	223.7
Skin	0	3	6
Initial Reservoir Pressure, kPa	65,397	81,744	98,092
Formation thickness, m	23.3	29.1	34.9
Reservoir radius, m	1112	1390	1668

Figure 3 shows the Pareto chart of the Plackett–Burman analysis. As expected, permeability is the most influential variable. The vertical line signifies that these results are within the 95% confidence interval. Four of the selected variables—permeability, initial reservoir pressure, formation thickness, and skin, could affect the cumulative production loss significantly. Therefore, when the environmental impact led by blowout event is evaluated, these variables need to be obtained carefully.

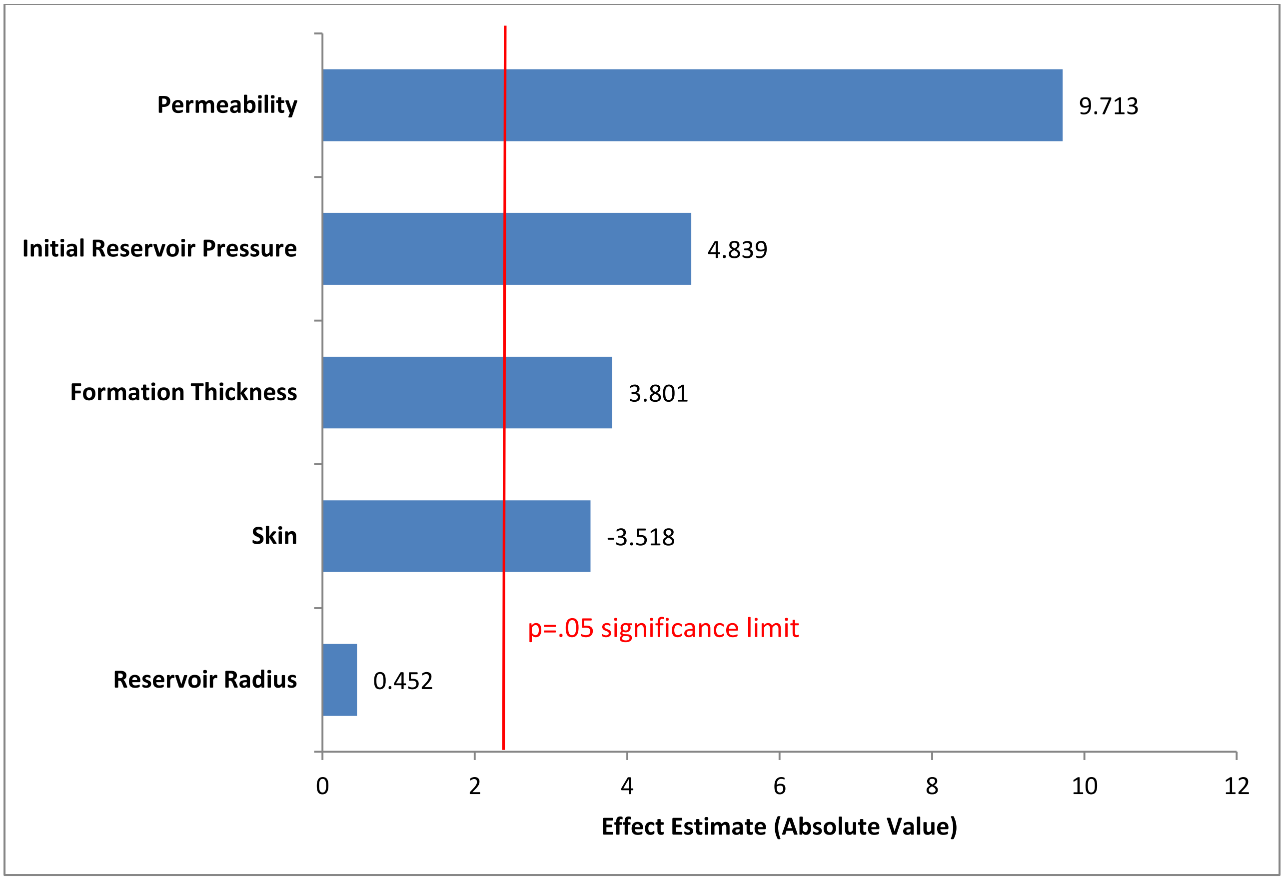

Figure 3. Influences of selected variables for Plackett–Burman design

The hazard during the initial stage of the Macondo incident is also studied in this paper. We assume that there was no constraint at the platform (*e.g.*, separator) for the simplicity, so that the formation fluid was released directly to the drilling rig. The changes of pressure and temperature led to different gas volume fractions at various depths along the wellbore. If the reservoir pressure is higher than the bubble point pressure, a single phase oil flow that contains a large amount of gas can be expected at the bottomhole, which is what happened in the Macondo incident. When the fluid flows upward, the pressure will gradually drop. As the pressure drops below the bubble point pressure, the gas contained in the oil phase will start to come out from the mixture, resulting in bubbly flow. If the pressure drops further with upward movement of the fluid, more and more gas will form from the mixture, eventually leading to single phase gas at the wellhead.

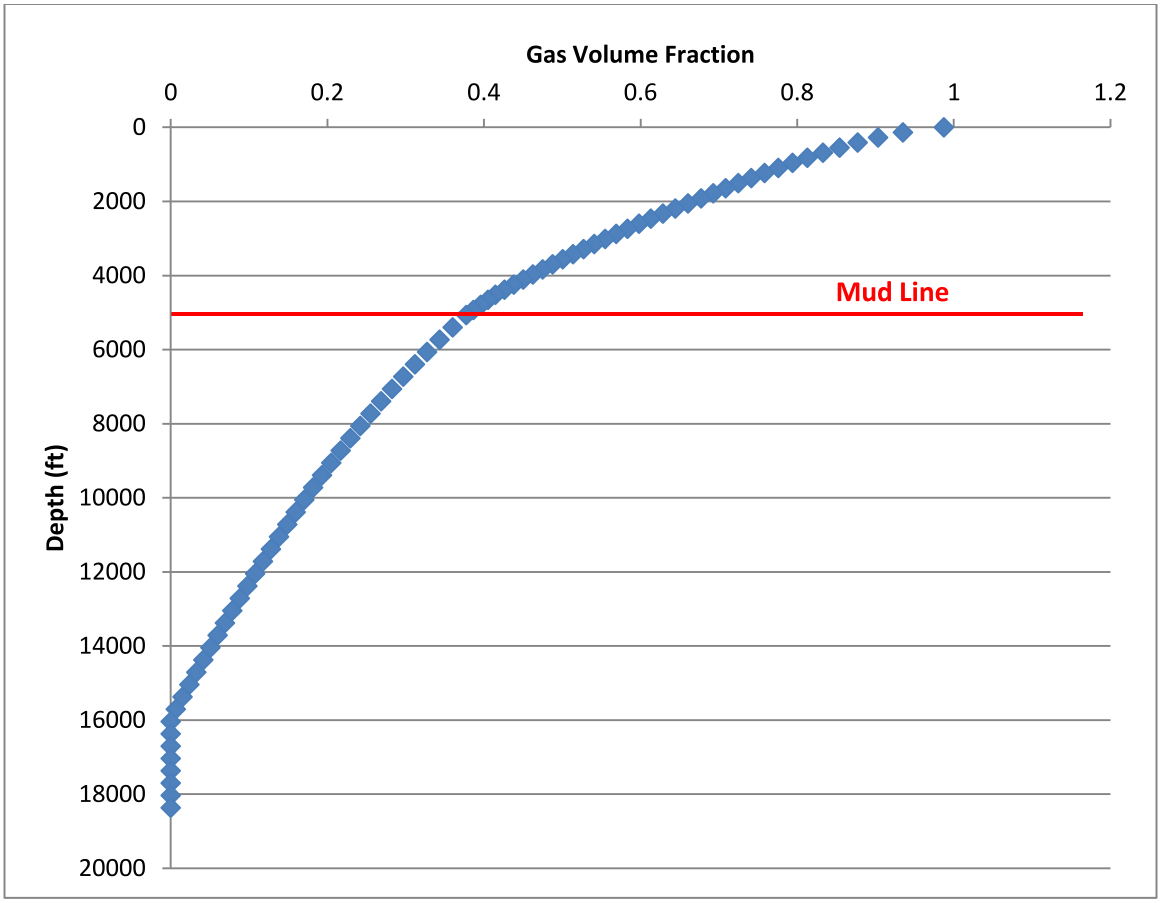

Figure 4. Gas volume fraction along the wellbore

Figure 4 shows how the gas volume fraction changes for the Macondo well. The formation fluid is single phase oil near the bottomhole of the well as the reservoirs in the US GOM are generally overpressure. As it moves upward, the gas starts to release from the oil phase. The gas volume fraction increases rapidly above the mud line until it equals one. It indicates that the main composition of the formation fluid coming to the drilling rig is gas. Given the conditions when the incident happened, the prediction of our blowout simulator shows that the sonic flow exists. The velocity of the fluid at the wellhead reaches 489.5 m/s. This high velocity of the formation fluid results in a quick dispersion at the drilling rig, and explains why the explosion happened only in several minutes.

Conclusion

Blowout events have caused many deadly incidents with a number of fatalities and financial losses for more than one century. Such events also have devastatingly damaged the environment. However, we still cannot perform a comprehensive risk assessment and consequence analysis of blowout events due to the lack of understanding of its mechanisms. Particularly for the aftermath calculation, the estimation of oil spill volume has to rely on the incident data (barrels of oil recovered, flame or plume height).

The analytical blowout simulator presented in this paper is helpful to understand the blowout mechanism. To capture all the physical phenomena during a blowout event, blowouts need to be simulated from the beginning of the event to the time they are brought under control. The model could be used to estimate the blowout rates as a function of time and corresponding volume of spill based on the parameters of the reservoir and the wellbore and other operational conditions.

Another advantage of this model is to provide information to contribute to consequence analysis. The spill rate and volume would be coupled with environmental conditions (speed of wind and temperature) to identify the risks associated with fires, toxic gases, and explosions during a blowout event when the well is designed. Moreover, proper well control strategies could be developed based on the model. The rate of killing fluid and the capacity of the corresponding pump can also be estimated.

Nomenclature

p	Pressure, kPa
γ	Heat capacity ratio
c	Sonic velocity, m/s
R	Gas constant, J/(K mol)
M	Molecular weight, g/mol
T	Temperature, K
E	Bulk modulus elasticity, Pa
ρ	Density, kg/m^3
f	Volume fraction
L	Liquid
g	Gas

SI Metric Conversion Factors

STB × 6.289 811 = m^3

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