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Analytical model to control off-bottom blowouts utilizing the concept of simultaneous dynamic seal and bullheading

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ANALYTICAL MODEL TO CONTROL OFF - BOTTOM BLOWOUTS
UTILIZING THE CONCEPT OF SIMULTANEOUS DYNAMIC SEAL
AND BULLHEADING

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in Partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Petroleum Engineering

by

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August 2002
DEDICATION

I wish to dedicate this work to my mother for her love and prayer, to my wife for her understanding and support during all the time that this research was being developed, and especially to my daughter, Valeria for her inspiration and encouragement.
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NOMENCLATURE

\[ A = \text{area of flow, ft}^2 \]
\[ A_{an} = \text{area of annulus, in}^2 \]
\[ A_{ds} = \text{area of drill string, in}^2 \]
\[ B_g = \text{gas volume factor, ft}^3/\text{scf} \]
\[ C = \text{gas rate flowing into the productive zone by pressure change, Mscf/day-psi} \]
\[ c_g = \text{compressibility of the gas, psi}^{-1} \]
\[ c_r = \text{reduced isothermal compressibility, dimensionless} \]
\[ c_t = \text{total compressibility, psi}^{-1} \]
\[ D_v = \text{vertical depth, ft} \]
\[ d = \text{diameter of the pipe, in} \]
\[ d_1 = \text{outer diameter of the pipe, in} \]
\[ d_2 = \text{inner diameter of the pipe or borehole, in} \]
\[ d_e = \text{equivalent diameter, in} \]
\[ d_{erw} = \text{diameter of the relief well, in} \]
\[ d_h = \text{hydraulic diameter, in} \]
\[ d_i = \text{diameter of the pipe, ft} \]
\[ d_{max} = \text{maximum droplet size, ft} \]
\[ F = \text{factor to account for effect of turbulence on } K_d, \text{ dimensionless} \]
\[ f = \text{Moody friction factor, dimensionless} \]
\( f' \) = Fanning friction factor, dimensionless

\( g \) = gravity acceleration, ft/sec^2

\( g_c \) = conversion factor 32.2 lbm-ft/lbf-sec^2

\( H \) = vertical depth of the well, ft

\( HHP \) = hydraulic horse power, hp

\( h \) = net pay thickness, ft

\( i_{bf} \) = injection flow rate, ft^3/sec

\( J \) = productivity index, gal/min-psi

\( K \) = resistance coefficient

\( K \) = consistency index of the fluid, eq cp

\( K_d \) = drag coefficient, dimensionless

\( k \) = effective formation permeability, md

\( L \) = section length, ft

\( M_a \) = molecular weight of air, 28.96

\( M_g \) = momentum of the gas, lbf

\( \dot{M}_g \) = molecular weight of gas

\( M_{bf} \) = momentum of the kill fluid, lbf

\( N \) = speed of the rotational viscometer, rpm

\( N_{Re} \) = Reynolds number, dimensionless

\( n \) = flow behavior index, dimensionless

\( p \) = pressure, psia

\( p_{ann} \) = surface pressure in the relief well, psi
\( p_{bh} \) = bottomhole pressure, psi
\( p_F \) = formation fracture pressure, psi
\( p_f \) = frictional pressure losses, psi
\( p_h \) = hydrostatic pressure, psi
\( p_i \) = pressure at the top of the cell, psi
\( p_{l\text{-}last} \) = pressure at the top of the last cell, psi
\( p_{int} \) = pressure at the interface (kill fluid - formation gas), psi
\( p_n \) = pressure at interest depth, psia
\( p_{pc} \) = pseudo critical pressure, psia
\( p_{pr} \) = pseudo reduced pressure, dimensionless
\( p_R \) = reservoir pressure, psi
\( p_s \) = surface pressure, psi
\( p_{sd} \) = pressure at the injection string depth (kill fluid - formation gas), psi
\( p_{wf} \) = bottomhole flowing pressure, psi
\( p(0) \) = bottomhole pressure at time 0, psi
\( p(t) \) = bottomhole pressure at time \( t \), psi
\( dp/dL \) = pressure gradient, psi/ft
\( q_{crit} \) = critical gas flow rate, MMscf/day
\( q_g \) = in-situ gas flow rate, ft\(^3\)/day
\( q_{gb} \) = gas flow rate flowing into the formation at the bullheading process, Mscf/day
\[ q_{gsc} = \text{gas flow rate at standard conditions, scf/sec} \]
\[ q_{gscd} = \text{gas flow rate at standard conditions, scf/day} \]
\[ q_{kf} = \text{kill flow rate, bpm} \]
\[ q_{kfb} = \text{kill flow rate at the bullheading process, ft}^3/\text{day} \]
\[ q_{kfOH} = \text{kill rate for minimum volume, gpm} \]
\[ q_{kf\infty} = \text{kill rate for infinity kill volume, gpm} \]
\[ q_{Mhf} = \text{momentum kill flow rate, ft}^3/\text{sec} \]
\[ q_{rw} = \text{kill flow rate on the relief well, bpm} \]
\[ R = \text{universal gas constant, 10.732 psia-ft}^3/\text{lbm-}^\circ\text{R} \]
\[ R_f = \text{ratio of frictional drag, dimensionless} \]
\[ r_e = \text{drainage radius, ft} \]
\[ r_w = \text{wellbore radius, ft} \]
\[ T = \text{temperature, } ^\circ\text{R} \]
\[ T_n = \text{temperature at interest depth, } ^\circ\text{R} \]
\[ T_{pc} = \text{pseudo critical temperature, } ^\circ\text{R} \]
\[ T_{pr} = \text{pseudo reduced temperature, dimensionless} \]
\[ t = \text{time, hr} \]
\[ t_k = \text{kill time, sec} \]
\[ V_{an} = \text{annular volume, gal} \]
\[ V_g = \text{volume of gas flowing in an open formation, Mscf} \]
\( V_{kf} \) = volume of kill fluid pumped into the well, ft\(^3\)

\( V_i \) = well volume, ft\(^3\)

\( v \) = velocity of the fluid, ft/sec

\( v_c \) = average velocity of the gas continuous phase, ft/sec

\( v_{crit} \) = critical gas velocity, ft/sec

\( v_{kf} \) = velocity of the kill fluid, ft/sec

\( v_m \) = velocity of the mixture, ft/sec

\( W_s \) = weight of drillstring in air, lb

\( z_{\bar{p}} \) = gas compressibility factor at average pressure, dimensionless

\( z_n \) = gas compressibility factor at interest depth, dimensionless

\( z \) = gas compressibility factor, dimensionless

**Greek Letters**

\( \alpha \) = fraction of the gas, fraction

\( \beta \) = turbulence factor, 1/ft

\( \Delta L \) = length increment, ft

\( \Delta p_0 \) = initial or first pressure increment, psi

\( \Delta p_1 \) = final pressure increment, psi

\( \Delta T \) = temperature increment, °F

\( \varepsilon \) = absolute roughness, in

\( \varepsilon \) = convergence tolerance

\( \phi \) = total porosity, fraction
\( \gamma_g \) = gas specific gravity, dimensionless
\( \lambda \) = fraction of the liquid, fraction
\( \mu \) = viscosity of the fluid, cp
\( \mu_a \) = apparent viscosity, cp
\( \mu_c \) = viscosity of the gas continuous phase, lbm/ft-sec
\( \mu_d \) = viscosity of the liquid phase, lbm/ft-sec
\( \mu_g \) = viscosity of the gas, cp
\( \mu_{kf} \) = viscosity of the kill fluid, cp
\( \mu_m \) = viscosity of the mixture, cp
\( \mu_1 \) = gas viscosity at one atmosphere and reservoir temperature, cp
\( \theta_N \) = dial reading of the rotational viscometer at N rpm
\( \rho \) = density of the fluid, lbm/ft\(^3\)
\( \rho_c \) = density of the gas continuous phase, lbm/ft\(^3\)
\( \rho_d \) = density of the liquid phase, lbm/ft\(^3\)
\( \rho_g \) = density of the gas, lbm/ft\(^3\)
\( \rho_{gsc} \) = density of the gas at standard conditions, lbm/ft\(^3\)
\( \rho_{if} \) = density of the influx fluid, ppg
\( \rho_{ikf} \) = density of the initial kill fluid, ppg
\( \rho_{sf} \) = density of the kill fluid, lbm/ft\(^3\)
\( \rho_m \) = density of the mixture, lbm/ft\(^3\)
\[ \rho_{mw} = \text{density of the mud weight in use, ppg} \]
\[ \rho_{pr} = \text{pseudo reduced density, dimensionless} \]
\[ \sigma = \text{surface tension, dyne/cm} \]

**Subscripts**

\[ acc = \text{acceleration} \]
\[ an = \text{annulus} \]
\[ bw = \text{blowout well} \]
\[ el = \text{elevation} \]
\[ f = \text{friction} \]
\[ kf = \text{kill fluid} \]
\[ n = \text{interest depth} \]
\[ R = \text{reservoir} \]
\[ rw = \text{relief well} \]
\[ t = \text{total} \]
ABSTRACT

The current methods for off-bottom control of blowouts involve pumping kill fluid into the well through an injection string. These are the dynamic kill and the momentum kill.

The dynamic kill, which is based on the steady state system analysis approach, and the momentum kill, that is loosely based on the Newton’s Second Law of Motion, have been used extensively in off-bottom control of actual blowouts. A comprehensive study of these two concepts was performed. The review included an analytical analysis of the published design techniques for both of these methods. The application of these techniques to several different field and hypothetical cases were compared. The study drew conclusions about the conceptual validity, applications, advantages, substantial shortcomings, and design problems for each method.

In this work, an alternative method for controlling an off-bottom blowout was also developed. The method is based on the dynamic kill and bullheading concepts and is called "dynamic seal - bullheading". Conceptually, the method involves two important stages in the control process. First, a dynamic seal is established at the injection string depth. Second, this forces a portion of the kill fluid to flow downward displacing, equivalent to bullheading, the remaining formation fluid in the wellbore back into an open formation. The models for each stage of this method were implemented in a computer program to give a design method for estimating the kill parameters such as kill flow rate, kill fluid density, kill fluid volume, pumping time and effect of control depth. The program also calculates the formation fluid influx, surface pressure, bottomhole pressure, and pressure at critical points in the well as a function of time during the control.

The proposed method and the conventional dynamic control method were compared for two different off-bottom blowout scenarios using the new computer program. The first scenario is an actual field case and the second is a hypothetical blowout with input data from a real well configuration and reservoir.
In both cases, dynamic seal - bullheading would provide a more reliable and conclusive kill in a minimum period of time.
CHAPTER 1

INTRODUCTION

Despite good drilling and production well planning, the availability of modern drilling equipment, such as measurement while drilling and sophisticated kick detection systems, and appropriate crew training, blowouts still occur. Combinations of equipment failure, geological uncertainties such as unexpected higher formation pressure or lost circulation zones, and human error lead to these incidents.

1.1 Blowout Definition

A blowout is defined as an uncontrolled flow of formation fluids from a wellhead or wellbore. It represents the most feared and unwanted phenomenon that might result from drilling or other well operations. Blowouts take place worldwide under a wide range of geological, operational, and geographical conditions.

In drilling, completion and workover operations, a kick occurs whenever the wellbore pressure caused by the wellbore fluids is less than formation pressure in an exposed zone capable of producing fluids. The specific causes of kicks, and of abnormal pressure that is a common cause of kicks, are described in many references, including Bourgoyne¹. The rate of the fluid influx is proportional to the flow capacity of producing zone and to the pressure differential between the formation and the wellbore. An appropriate well control procedure must be performed to remove the kick fluids and avoid additional formation fluid from flowing into the well. Unfortunately, control attempts are not always successful, and lost of control of the well typically result in a blowout.

On the other hand in production operations, the principal reason for loss of well control is an equipment failure due to external forces (hurricane, storm, ship
collision, dropped object, etc.), material defect, fatigue, corrosion, sand erosion or H₂S embrittlement. Logically, the inherent uncertainty of such events implies that some probability of a blowout results from any operation on or production from a well that is flowing.

There are several types of blowouts, such as a surface wellhead blowout, an underground blowout, and an underwater blowout. Surface blowouts are very dangerous because they cause an immediate risk to the crew, equipment and environment, since the formation fluids are freely flowing to the atmosphere. An underground blowout is defined as the uncontrolled flow of formation fluids from one stratum to another stratum, so its manifestation is hidden from view. This kind of flow happens when a kick is taken and a fracture or lost circulation occurs in the wellbore, potentially causing overpressuring of shallow formations, cratering, or other problems. In an underwater blowout, the formation fluids flow from the subsurface formation to the sea floor. This problem can potentially cause significant environmental damage.

1.2 Blowout Consequences

Blowout consequences are frequently disastrous and extremely expensive. These consequences include

♦ Environmental damage,
♦ Reservoir depletion,
♦ Loss of hydrocarbon reserves,
♦ Water coning (in bottom-water reservoirs),
♦ Safety risk due to the flow of dangerous (flammable and potentially toxic) formation fluids (gas, oil, salt water and/or hydrogen sulfide),
♦ Loss of equipment and materials,
♦ Blowout control cost,
♦ Loss of the operator's and personnel's credibility, and
♦ Loss of human lives or injuries,
1.3 Blowout Control Intervention Techniques

There are also different intervention techniques to control blowouts. Some are applicable only in certain situations. The most common are:

- **Capping**

  Capping is practically a mechanical shut-in, which involves installing a special BOP or valve assembly on the well. This technique requires access to the well. Therefore, any debris and damaged structures must be removed before starting the operations. Generally, any fire should then be extinguished, if the formation fluids do not contain H₂S, to allow an easier and safer operation. Next, the wellhead and the blowout preventers or tree must be inspected to determine whether they can be used to provide a high pressure connection to the capping stack or if they should be removed, and a new connection installed. Once a sound connection exists on the well, the open capping stack is placed over the well, lowered on to the connection on top of the well, and attached to the well. The blind ram is then closed to either divert the flow or shut the well in. At this point, an appropriate well control technique like bullheading, lubrication or snubbing pipe or coiled tubing into the well for a more conventional kill can be applied.

  Figure 1.1 shows a typical capping operation. Illustration (a) displays when the well is flowing without control and the capping assembly is ready to be placed. Illustration (b) shows when the capping assembly and valves have been positioned on the wellhead and the bolts have been torqued up. In illustration (c) the blind ram is closed, and the flow is diverted. Illustration (d) exhibits when the valve is closed and flow from the wellbore is stopped. A simplified adaptation of the shut-in capping method has been successfully applied to low pressure wells. It involves stabbing a stinger with seals into the top of the flowing well and then bullheading the well through the stinger.
Capping cannot be undertaken if there is not access to the well, or if the well has cratered. Capping operations are more difficult if the well is on fire.

![Figure 1.1 Typical capping operation](image)

**Figure 1.1** Typical capping operation
Another possibility for controlling a blowout is to drill a relief well to provide a flow path to pump kill fluids into the blowout well. This technique requires drilling a directional well to intersect the blowout well and establish a flow connection between the two wells. Then, either of two techniques can be used to bring the formation flow under control and extinguish any fire. The first is an on-bottom dynamic kill, which is carried out by pumping kill fluid at enough rate so that the sum of the frictional and hydrostatic pressures exceeds the formation pressure. The second is reservoir flooding, which is basically a matrix flood of the near well reservoir with water to block further influx of oil and gas. This method is depicted in Figure 1.2.

Figure 1.2 Relief well intervention technique
The most critical factor in the relief well method is the flow connection. If there is not a good connection between the wellbores, or to the reservoir around the well, the kill operation will be practically impossible. This type of well control intervention is extremely expensive and time consuming because it requires drilling on additional well. Consequently, the impact of the blowout is experienced over an extended period of time.

♦ Surface intervention through an injection string

It may be possible to regain the control of the well by pumping kill fluid through an injection string or through the annular section between the inner string and casing from the surface. This intervention technique requires a string (drill pipe, drill collars, work string, casing, tubing, etc) be present in the well to have a circulation path from the surface to some point within the wellbore. This is frequently possible because most blowouts occur with at least some kind of pipe in the well. There are two engineering designs available in the oil industry to calculate the control parameters using the surface intervention through an injection string; they are the momentum kill and the dynamic kill. These methods will be discussed further in Chapter 3.

Comparing the three intervention techniques (capping, relief well and surface intervention) previously presented, surface intervention is typically a more convenient, easier, faster and cheaper method to regain the control of a blowout well. If applicable, it can be used just after the blowout begins. Figure 1.3 shows a schematic diagram of this technique.

It is really important to point out that most of the well control plans consider at least two techniques to control the blowout, therefore the blowout contingency planning should consider the preparation for drilling one or two relief wells even if surface killing or capping are being carried out.

This research will primarily focus on control of surface wellhead blowouts by pumping a control fluid through an off-bottom injection string from the surface to the wellbore. In cases where this method is applicable, it can be accomplished
more economically and faster than an intervention through relief well. Hence, the blowout consequences can be substantially reduced.

Figure 1.3 Surface intervention through an injection string

1.4 Conventional Well Control Procedures

Several well control-engineering designs are available in the literature, which are subdivided into conventional and non-conventional procedures. The conventional ones apply a constant bottom hole pressure concept, in which the pressure at the bottom is maintained slightly greater than formation pressure throughout the complete control procedure trying to meet two aims simultaneously. The first is to keep the formation from flowing while displacing the initial influx to the surface, and the second is to avoid the possibility of breaking down the formation at its weakest point and initiating an underground
blowout. The classical, conventional methods that employ this principle are
driller's method, wait and weight method, and concurrent method.

All of these techniques require controlling the surface pressures on the
well to keep bottomhole pressure constant and having the drillstring or workstring
near the kick zone. Consequently, these methods are not applicable to the off-bottom blowout conditions on which this study focuses.

1.5 Off - Bottom Well Control Complications

For conventional well control procedures to be employed, the string must
be on-bottom or near bottom. Otherwise, it is not assured that the kick fluids will
be circulated out of the well and replaced with kill density fluids since there is no
circulation path to displace the formation fluid with kill fluid. An off-bottom scenario is shown in Figure 1.4.

![Figure 1.4 - In off-bottom scenarios the mixture (formation and kill fluid) properties below of the injection point are unknown.](image)
In off-bottom operations, the surface pressure will not reflect conditions at the bottom of the hole directly, and the constant pressure concept is very difficult to apply because the fluid types, properties, and densities below the injection point are not conclusively known.

In traditional well operations like drilling, completion and workover, the necessity to make trips with the drill string or run casing or tubing is unavoidable. A large percent of well kicks occur during these operations. One of several reasons is that when the pump is stopped to begin a trip the effect of friction increasing the equivalent circulation density is gone. In addition, when the bit starts to leave the bottom it can generate a swabbing effect and a temporary reduction in pressure. Either or both of these may cause the well to be underbalanced, Thus, some gas may flow into the wellbore reducing the hydrostatic head due to its low density and due to expansion while migrating upward. Well control problems have also occurred when the drill string is lowered too fast, breaking down the formation and causing loss of mud. The drilling fluid level falls causing a reduction of the hydrostatic pressure. Hence, the well control procedure must be carried out with the string partially out of the well, in other words, in off-bottom conditions.

Another off-bottom situation is presented when the string has parted or has washed out. As mentioned earlier, under those circumstances, the conventional well control techniques cannot be applied. According to Grace, "there is no classical well control procedure that applies to circulating with string off-bottom with a formation influx in the wellbore, and the concepts, technology and terminology of classical well control have no meaning or application in these circumstances". Therefore, it is more likely to have blowouts during tripping or off-bottom operations, because it is more difficult to control a well in off-bottom conditions than in on-bottom ones.
1.6 Non-Conventional Well Control Procedures

Well control situations that occur when pipe is off-bottom or when surface pressure containment is not possible cannot be controlled using the classical methods. Therefore, non-conventional well control procedures have been adopted for these conditions.

Two non-conventional well control methods can only be used when the well is shut in and the pressure can be contained by the surface well equipment (wellhead, preventers, valves, etc). These are lubrication after volumetric control and bullheading. Either can be applied to both on and off-bottom situations. On the other hand, dynamic and momentum kill are the only two methods reported in the literature that can be utilized to control surface blowouts where the well cannot be shut in at the surface. The dynamic method can be applied to both on and off-bottom situations. The momentum kill method is conceptually most applicable to off-bottom situations. Each method is introduced in the following paragraphs.

- **Lubrication after volumetric control**

  Volumetric control is an adaptation of the constant bottom hole pressure concept to conditions where the well cannot be circulated. After a gas kick is taken the difference in densities between gas and drilling mud causes upward gas migration generating an increase in pressure in the entire well because gas expansion is not possible. The pressure increase can result in formation breakdown or well equipment damage causing a surface blowout or underground blowout if it is not controlled. Volumetric control allows gas expansion in a controlled manner, keeping the bottom hole pressure slightly above the formation pressure to prevent further influxes from the producing zone to the wellbore.

  Volumetric control is performed by bleeding a computed volume of mud through the choke to reduce well pressures. This bleeding procedure is repeated to control the pressure in the system within a pre-defined range. It is completed when all of the gas has reached the surface, stopping the pressure increase in
the well. A related procedure, known as lubrication, can inject mud at the surface to replace the gas while keeping a controlled pressure at the bottom. A previously calculated kill mud volume is injected from the surface and falls through the gas. Then, only gas is bled off until the surface pressure reaches a pre-established value. Ideally, this procedure is iterated until that the well is completely filled with mud.

- **Bullheading**

  In the bullheading technique, the formation pressure is intentionally exceeded by pumping kill fluid from the surface down the well forcing the formation fluid back into the reservoir or other subsurface formation. A surface shut in is required and a pressure analysis of the system must be done, since the pressures applied by the pump and the hydrostatic column may damage the integrity of the well's casing, tubing, wellhead, blowout preventers, or valves generating a surface or underground blowout. A detailed description of this technique, as well as the derivation of a mathematical model to compute the control parameters, is presented in Chapter 4.

- **Dynamic kill**

  The dynamic kill is a procedure that can be used to regain control of a surface or underground blowout. It involves pumping kill fluid through either a relief well or an injection string into the blowing well. The pump rate used must create enough back pressure due to the frictional pressure losses and increases in hydrostatic pressure due to the multiphase flow of formation and kill fluid to exceed the shut in formation pressure and stop the gas flow. Dynamic kills have proven successful in both on-bottom and off-bottom blowouts. However, off-bottom conditions present some uncertainty because conditions below the injection point are not precisely known or controlled. Previous research on this method is described in Chapter 2. The detailed method, as well as its main problems in the off-bottom scenario, are explained in Chapter 3.
Momentum kill

The momentum kill concept has been also proposed\(^2\) as a method to recover control of a surface blowout. It involves injecting kill fluid downward into the blowout well through an injection string from the surface. The formation fluid and the kill fluid will collide at the injection string depth. The concept is that if the momentum of the control fluid is greater than the momentum of the formation fluid, it will stop the blowout fluid and force it to go back into the producing zone and bring the well under control. The concept and a mathematical model of this technique are discussed in Chapter 3.

Although these non-conventional procedures to control surface and underground blowouts have been applied successfully, shortcomings in the design methods exist for both momentum and off-bottom dynamic kills. Therefore, further analysis of and improvements to these blowout control methods and the investigation of new procedures is desirable and is presented in Chapter 3.

1.7 Objectives of Research

The oil and gas industry does not presently have a rigorous and fully developed engineering design procedure to analyze and design an off-bottom blowout control process. This is despite the fact that almost 40% of the analyzed blowouts from 1980 through 1994 in the Gulf of Mexico, the U.S., Norway, and United Kingdom\(^5\) were in an off-bottom condition. Hence, this research is concentrated with developing a procedure and engineering design to control oil and gas blowouts with the injection string off-bottom. The principal objectives to achieve this goal are the following:

1. Review the current off-bottom blowout control techniques available in the literature, document the operational, design, and analytical procedures applicable to these techniques, and describe their applications, advantages, operational deficiencies, limitations and design problems.
2. Develop an alternative procedure combining the dynamic kill and bullheading concepts to control blowouts with the injection string (drill pipe, drill collars, work string casing, tubing, etc.) off-bottom. Create the engineering design method for this procedure that provides a basis for determining:

- Kill flow rate.
- Kill fluid density.
- Pressures in the system (surface, injection string depth, critical points in the wellbore and bottom).
- Effect of control depth.
- Time required.
- Kill fluid volume.

3. Compare the proposed method with the current off-bottom blowout control methods in order to determine their advantages, disadvantages and differences.

1.8 Scope of Research

The intense demand for oil and gas in the world is moving the industry in the direction of higher pressure and higher technology wells. These wells present additional technical challenges due to greater pressures, depths, and temperatures. The risk of occurrence and the magnitude of blowouts as well as the consequences are all likely to be more serious than for simpler wells. Therefore, the investigation of better procedures to control off-bottom blowouts in a rapid and effective way becomes increasingly important.

This research is primarily focused on an investigation of kill methods for regaining control of an off-bottom, surface blowout. The methods involve pumping kill fluid from the surface into the wellbore through an injection string such as drill pipe or workstring. This intervention technique can potentially be accomplished more economically and faster than the others such as capping or relief wells, thereby reducing control costs and blowout consequences.
The study presents an analysis and comparison of the two current off-bottom blowout control methods through an injection string described in the literature, momentum and dynamic kills. It also proposes an alternative procedure, including an engineering design method, to control off-bottom blowouts called "dynamic seal - bullheading" that is essentially a combination of the dynamic and bullheading concepts.
CHAPTER 2

LITERATURE REVIEW

This chapter begins with a review of historical blowout statistics. These provide context for the importance of blowouts in general and of off-bottom, gas blowouts in particular. This chapter then presents the current models in the oil and gas industry that can be used to analyze and design a blowout control by pumping kill fluid through a tubular conduit in the well. The models are categorized as steady and unsteady state models.

The principal difference between a steady state model and an unsteady state, complex model is that the first one does not compute the required kill mud volume to regain the control of the well, since it does not involve the kill time. However, both models practically yield the same results for the other kill parameters such as kill flow rate, and kill density.

2.1 Blowout Statistics and Trends

This section reviews two blowout statistical analyses to emphasize several important aspects about these catastrophes. The data include blowout frequencies and meaningful trends like the operational phase (drilling, completion, workover, production, etc), the actual activity (drilling, tripping, casing running, cementing, perforating, etc.), blowing fluid type, blowout duration, and blowout consequences. The blowout databases in this study come from two independent sources.

Skalle et al. present 1120 blowout events from the Gulf of Mexico and the adjoining states in U.S. (826 in Texas, 187 in the Outer Continental Shelf and the remaining 110 from Louisiana, Mississippi and Alabama) covering the period 1960-1996. The data were taken from the State Oil and Gas Board of Alabama,
Louisiana Office of Conservation, Mississippi State Oil and Gas Board, Texas Railroad Commission and Mineral Management Service.

Holand⁵ is based on his Ph.D. dissertation from the Norwegian University of Science and Technology. It presents 124 offshore blowouts that occurred on the outer continental shelf of the U.S. Gulf of Mexico and in Norwegian and United Kingdom waters in the period from January 1980 to January 1994. The data is from the SINTEF Offshore Blowout Database.

Table 2.1 shows the number of blowouts that occurred during the different operational phases per Holand⁵. It reveals that most blowouts occur during drilling (82 events, 66%). It should further be noted that workover blowouts (19 events, 15%) have occurred more often than completion and production blowouts. It was calculated that a blowout occurred once in every 162 wells for exploration drilling and in every 291 wells for development drilling.

Table 2.1 Number of blowouts during operational phase (Holand⁵)

<table>
<thead>
<tr>
<th>Area</th>
<th>Norway</th>
<th>UK</th>
<th>US GoM</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exploration</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drilling</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Shallow</td>
<td>7</td>
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<tr>
<td>Deep</td>
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<td>11</td>
<td>18</td>
</tr>
<tr>
<td>Development</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drilling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow</td>
<td>1</td>
<td>2</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>Deep</td>
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<td>1</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Completion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Workover</td>
<td>1</td>
<td>--</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Production</td>
<td></td>
<td>2</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Wireline</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Unknown</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>9</td>
<td>101</td>
<td>124</td>
</tr>
</tbody>
</table>

During the different phases, the following operations and activities were most frequently in progress when the blowouts occurred.
- Drilling: actual drilling (29%), tripping (24%), casing running (20%).
- Completion: tripping (28%), perforating (14%), gravel-pack (14%), killing (14%).
- Workover: pulling tubing (32%), circulating (16%), tripping (11%), perforating (5%).
- Production: equipment failure (50%), damage due to external forces (50%).

It can be seen from the above information that a significant fraction of all blowouts may occur when the string is off bottom. The database shows that 37% of the blowouts occurred during tripping, casing running, or pulling tubing. Therefore, off-bottom blowout control was probably required. Consequently, research on off-bottom blowout control methods and engineering designs is extremely important to the oil and gas industry.

Another meaningful trend involves the blowout fluid, which may be gas, a gas-liquid mixture, or liquid. Figure 2.1 shows the difference in fluid types in the study by Skalle et al.4.

![Figure 2.1 Number of blowouts with different blowing fluids (Skalle et al.4)](image)
On the other hand, Figure 2.2 displays the difference in fluid types in Holand’s study.5

![Figure 2.2 Number of blowouts with different blowing fluids (Holand5)](image)

Evidently, gas is by far the most dominant produced fluid in a blowout. The database from Skalle et al4 reveals that pure gas blowouts account for 55%. Flows of liquids occur in 9% blowouts, and 33% of the events involved a mixture of gas and liquids. On the other hand, Holand5 indicates that 77% were gas blowouts, 14% were a mixture of gas and liquid, and 3% were uncontrolled flow of liquid.

Blowout duration is another important characteristic that can be obtained from the statistical analysis. The duration of the blowout control depends on several factors. The most important are blowout severity, surface intervention plan, the availability of personnel, material, services and equipment, logistics plan, and blowout control technique and design. Unfortunately, it is almost impossible to separate and evaluate the effect of the above factors during a blowout control. Therefore, the databases present the blowout duration without specifying the most time consuming activity or factor.
Skalle et al. indicates that blowout duration has a wide range from 0 to 450 days. Figure 2.3 shows the cumulative percentage of blowouts versus duration. As seen, 46% of the blowouts were controlled in less than 24 hours, and 68% of the events were controlled in less than 3 days. More than 30% of the blowouts needed from 3 days to more than 30 days to regain the control. Additional analysis showed that the average duration is 519.6 hours for each blowout when the well depth is greater than 10000 ft.

![Cumulative Percentage vs Duration](image)

**Figure 2.3 Cumulative percentage of blowouts versus duration (Skalle et al.)**

Table 2.2 presents the duration of the various blowouts from Holland’s research. Holland considered that the blowouts with unknown duration had the same duration distribution as the blowouts with known durations. He concluded that 16% of all blowouts were controlled in less than 40 min, 21% lasted from 40 minutes to 12 hours, 44% lasted between 12 hours and 5 days, and 18% of the blowouts continued flowing more than 5 days.
As seen, the duration of blowouts ranges from hours to months. Therefore, all of the factors that take part during the intervention must be carefully analyzed. But special attention must be given to the blowout control technique and design, since it will practically be the last stage of the control, and if wrong kill parameters are selected, the entire blowout control plan will be unsuccessful. And as a consequence, the cost increases, and the blowout consequences continue.

All blowouts cause economic losses but sometimes the blowout cost is very large. As an example, the Treasure Saga blowout in the North Sea in 1989, which required more than 200 days of well control activities, had a cost of nearly $300 million dollars.  

Table 2.2 Duration of various blowouts (Holand$^5$)

<table>
<thead>
<tr>
<th>Time</th>
<th>&lt; 10 min</th>
<th>10-40 min</th>
<th>40 min- 2 hr</th>
<th>2-12 hr</th>
<th>12 hr- 5 day</th>
<th>&gt;5 day</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exploration Drilling</td>
<td>Shallow</td>
<td>--</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
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<td>1</td>
<td>2</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Development Drilling</td>
<td>Shallow</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Deep</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Completion</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>4</td>
<td>2</td>
<td>--</td>
</tr>
<tr>
<td>Workover</td>
<td>3</td>
<td>2</td>
<td>--</td>
<td>1</td>
<td>7</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Production</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>Wireline</td>
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<td>9</td>
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<td>7</td>
<td>14</td>
<td>43</td>
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</tr>
<tr>
<td></td>
<td>7.7%</td>
<td>6%</td>
<td>6%</td>
<td>12%</td>
<td>36.8%</td>
<td>15.4%</td>
<td>16.2%</td>
</tr>
</tbody>
</table>
2.2 Steady State Flow Models

---

E. M. Blount and E. Soeiinah (1981)

A landmark model for an on-bottom dynamic kill was presented by Blount and Soeiinah. It was used during kill operations on Mobil Oil Indonesia's prolific Arun blowout in 1978. They described a dynamic kill as a technique for terminating a blowout utilizing flowing frictional pressure to supplement the hydrostatic pressure of the kill fluid being injected through a communication link. Hence, the flow rate must be maintained such that the sum of frictional and hydrostatic pressure exceeds the static formation pressure and the well ceases to produce. They pointed out that it is really important to avoid breaking down the formation so the maximum amount of fluid can be circulated through the well increasing the flowing frictional pressure, and the opportunity to control the well. It was also advised to use two or more weights of mud, a light one to kill the well dynamically, then replacing it with a heavier one to kill the well hydrostatically.

Blount and Soeiinah proposed a simple model to find the necessary design parameters to carry out a dynamic kill with the drill string on-bottom. These kill parameters include:

Initial kill fluid density

They considered that the “initial dynamic kill fluid is to kill the well by exceeding the natural flow capacity of the wellbore”. The density of the initial kill fluid can be determined by the following equation.

\[
\rho_{ikf} = \frac{12.83 p_R}{D_v}
\]  

(2.1)

If the density of the initial kill fluid is lower than the density of the water, then water is used as the kill fluid in both dynamic and static condition.
Kill fluid injection rate

The required injection rate must generate a flowing frictional pressure to supplement the hydrostatic head of the kill fluid and exceed the static formation pressure. It is given by:

\[
q_{kf} = \left[ \frac{(p_R - p_b)k\epsilon^g}{11.41f_f L\rho_{bf}} \right]^{1/2}
\]

(2.2)

Where:

\[ p_b = 0.052\rho_{bf}D_f \]

(2.3)

The equivalent diameter, \(d_e\), is equal to the pipe diameter when the control fluid is pumped through the annular section. Contrarily, if the blowout control is carried out through the pipe and the flow is up the annulus the equivalent diameter becomes.

\[
d_e^5 = (d_2 - d_1)^3(d_2 + d_1)^2
\]

(2.4)

Fanning friction factor \(f_f\) in this procedure is calculated as follows.

\[
f_f = \frac{0.25}{\left[ 2\log\frac{d_h}{\epsilon} + 1.14 \right]^2}
\]

(2.5)

Here the hydraulic diameter \(d_h\) is defined by.

\[ d_h = d_2 - d_1 \]
Size of the relief well

Blount’s model\textsuperscript{32} considers a blowout control through both a relief well and by injecting kill fluid internally in the blowout well through the surface. Thus, if the first option is taken the relief well size should be considered in the kill plan since the relief well must have adequate flow capacity to allow dynamic control. This parameter is calculated by

\[
d_{e, rw} = \left[ \left( \frac{d_e^5 \Delta p_f}{f_j L} \right) \frac{f_j L}{\Delta p_f} \frac{1}{k^2} \right]^{1/5}
\]

Frictional pressure losses in the blowout well \( (\Delta p_f)_{bw} \) can be obtained as follows

\[
(\Delta p_f)_{bw} = p_R - p_h
\]

On the other hand, \((\Delta p_f)_{rw} \) represents the frictional pressure losses in the relief well and is calculated by

\[
(\Delta p_f)_{rw} = p_{ann} - p_F + p_{h, rw}
\]

Where \( p_{ann} \) is the surface pressure on the relief well, and \( p_F \) represents the fracture pressure of the formation. The term \( k \) stands for fraction of flow entering blowout well and is given by the ratio between the kill fluid injection rate \( q_{kf} \), flow up blowout well, and the injection rate required through annular section on the relief well \( q_{rw} \). It is mathematically represented by

\[
k = \frac{q_{kf}}{q_{rw}}
\]
Equivalent diameter in the relief well $d_{\text{rw}}$ is computed with equation 2.6. Then reasonable values of outside diameter of the pipe $d_1$ and casing diameter $d_2$ are calculated utilizing the equivalent diameter concept (Equation 2.4). If it was not planned to run a pipe in the relief well, the equivalent diameter $d_{\text{rw}}$ is the casing diameter $d_2$.

**Hydraulic horsepower**

The required hydraulic horsepower to pump the kill fluid with the needed kill rate is obtained by considering the maximum pump pressure $p_{\text{ann}}$. It is given by

$$HHP = \frac{q_{\text{rw}} P_{\text{ann}}}{40.81}$$  \hspace{1cm} (2.10)

**Maximum allowable BHP to prevent drill pipe from being ejected**

A force tending to eject the drill string from the blowout well is composed of the frictional drag and the hydraulic force acting on various cross sections of the drill string. The weight of the drillstring resists the ejection force. Therefore, if ejection force is greater than the weight, the pipe will be ejected. Accordingly, the maximum allowable bottom hole pressure to prevent this effect is computed by

$$p_{\text{blf max}} = \frac{W_s + A_{\text{ann}} R p_h}{A_{ds} + A_{\text{ann}} R}$$ \hspace{1cm} (2.11)

Ratio of the total frictional drag $R$ that applies to the drill pipe in the blowout well can be calculated as follows:

$$R = \frac{1}{2 \log \left( \frac{d_2}{d_1} \right)} - \frac{d_1^2}{d_2^2 - d_1^2}$$ \hspace{1cm} (2.12)
Blount and Soeiinah successfully used the above procedure to control an extremely difficult blowout in Indonesian's Arun field. The C-II-2 Arun well blew out and caught fire destroying the drilling rig and burned for 89 days at an approximate rate of 400 MMscfd. This method has been used for bringing several other blowouts under control around the world. It is important to point out that this method is intended to work when the drillstring is at the bottom of the well.

♦ R. D. Lynch et al. (1981)\(^{50}\)

Lynch et al utilized the steady state system analysis approach for a dynamic kill to bring under control a CO\(_2\), near-bottom blowout that occurred in 1982 in the Sheep Mountain Unit of Colorado. They considered that the following factors are of primary importance in the design of an on-bottom dynamic kill operation: bottomhole static formation pressure, pressure and hydraulic constraints, deliverability of the well, kill fluid density and injection rate.

The authors state that the selection of the kill fluid density is a trade-off between the advantages (higher hydrostatic and frictional pressure drops in the annulus) and disadvantages (higher friction pressure losses in the injection piping, which tend to reduce the injection rate) of a higher kill fluid density.

They found the required kill density and rate to control the blowout using the following steps. First, a reservoir model was used to calculate the reservoir performance curve (IPR). Then for a selected value of CO\(_2\) flow rate and selected value of kill fluid injection rate, the pressure distribution in the well was calculated (wellbore hydraulics performance). A series of such calculations yielded a plot of bottom hole pressure versus CO\(_2\) flow rate for various fixed values of kill fluid injection rate. Any wellbore hydraulics performance curve that lies entirely above the reservoir performance curve meets the conditions to control the well. Hence, the kill fluid density and injection rate utilized to construct that curve would be the ones that would kill the well.
Robert D. Grace (1987)⁸

Grace author utilized the momentum kill method to control the Wyoming off-bottom blowout. The momentum concept states that the momentum of the fluids flowing from the blowout must be overcome by the momentum of the kill fluids.

The well blew out in a washover and backoff operation. The annular preventer was closed and the formation fluid was flowing to the atmosphere through nine drill collars that extended from the above the rotary table to about 180 ft below it.

The well was controlled after calculating the momentum of the formation fluid, then the kill rate and density to overcome that momentum was obtained. The control operations were commenced by pumping the kill fluid through the annular section. The author concluded that when kill fluid intersected the flow stream at the end of the string, flow from the well ceased.


Koederitz et al developed a systematic technique for handling shallow gas flows based on an on-bottom dynamic kill. A high circulating rate is used to increase annular frictional pressure losses. The method estimates the loads on the wellbore and diverter system during the kill operation for a bottom supported marine rig, land rig, or a deep water-floating rig. The main goal is to avoid both underground fracturing, which may result in cratering and rig foundation problems, and failure of the diverter system. The authors presented the following procedure to apply this technique.

1. Plot the inflow performance of the reservoir to show flowing bottom hole pressure as a function of gas flow rate.
2. Superimpose on the plot of the step 1 the annular flow performance of the well for various liquid injection rates taking into account pressure change due to elevation, friction and acceleration.

3. Determine the kill injection rate from the plot as the line of constant injection rate which is just above the inflow performance line of the reservoir.

4. Plot the flowing annular pressure as a function of depth for various liquid injection rates up to the known kill injection rate.

5. Plot the casing seat depth and the fracture pressure as a function of depth on the graph of step 4. From the resulting plot, determine the fracture margin, which is defined as the minimum difference in the open hole interval between the fracture pressure and the annular wellbore pressure, expressed as an equivalent mud density.

6. Determine the frictional pressure losses in the injection string with and without friction reducers being present. The friction reducers are assumed to affect only the pressure losses in the injection string.

7. Determine surface injection pressure and hydraulic power requirements with and without friction reducers being present.

   Parameters such as kill fluid rate and density, injection pressure, injection horsepower, a wellbore pressure profile, and diverter wellhead pressure can be determined from this analysis procedure.

* Robert D. Grace and Bob Cudd (1989)*

The authors employed the momentum kill method in bringing the off-bottom South Louisiana blowout under control.

After six weeks of conventional control methods, they applied the momentum kill method to try to control the well. Hence, the required kill rate and kill density to overcome the momentum of the formation fluid was computed. Then the kill fluid was pumped into the well through an injection string. The blowout was controlled.
John D. Gillespie, Richard F. Morgan, and Thomas K. Perkins (1990)\textsuperscript{52}

Gillespie \textit{et al} proposed the first dynamic kill design that considered an off-bottom condition. They determined that the dynamic kill concept could be used to analyze a kill operation with the kill string at any position above the flow zone in a well. During a dynamic control operation, the mixture of kill and formation fluids flowing from the injection point to the surface generates a back pressure acting on the reservoir, which will reduce the formation flow rate. If that gas flow rate is reduced sufficiently, small droplets of the injected fluid will be able to fall through the gas with a velocity that exceeds the upward velocity of gas. In this counter-current flow condition, the kill fluid will accumulate below of the injection depth increasing the hydrostatic head opposing the flow.

The authors determined that the countercurrent flow of injected liquid droplets falling through the gas flow depends mainly on the maximum stable droplet size and the maximum drag coefficient. Hence, they proposed three methods to estimate the maximum droplet size, \( d_{\text{max}} \), and an equation to calculate the drag coefficient, \( K_d \). Finally, they presented an equation to calculate the critical gas velocity, \( v_{\text{crit}} \), which is the gas velocity that is just incapable of sweeping out the maximum droplet size. In other words, gas velocities greater than this critical value would lift all droplets out of the well. This equation is given by:

\[
v_{\text{crit}} = \sqrt[3]{\frac{4g d_{\text{max}} (\rho_{\text{sf}} - \rho_g)}{3 \rho_g K_d}} \quad (2.13)
\]

From this analysis, there is no way to know the liquid accumulation in the lower part of the well during the control. Consequently, the gas and liquid fraction in that zone is unknown. Therefore, the bottom hole conditions (pressure and formation rate) cannot be completely predicted.
David Watson and Preston Moore (1993)\textsuperscript{7}

David Watson \textit{et al} consider that the momentum kill method can help in quickly regaining control of blowing well and it is an attractive technique for controlling a well because it can save money, time effort and natural resources compared to other blowout control methods.

The authors indicate that the desired result of a momentum kill is a state equilibrium at the point of impact. That is that the fluid velocity in each opposing system reduces to zero, and the resultant vertical forces for two fluids are equal but act in opposite directions.

Watson \textit{et al} presented a complete procedure to apply this method. The procedure includes equations to calculate momentum of the formation fluid, optimum kill string, kill fluid and pump rate, and minimum depth necessary to place the kill string. Also a numerical example of the momentum kill is given.

G. E. Kouba, G. R. MacDougall, and B. W. Schumacher (1993)\textsuperscript{33}

Kouba \textit{et al} presented three methods to determine the upper and lower limits of the injection rate needed to dynamically kill a well. These include a technique for establishing a conservative most probable minimum kill rate. A method for estimating the liquid accumulation below the injection point in an off-bottom kill was also proposed.

\textbf{Multiphase Flow Solution.}

They determined that the basic idea of this solution is that, for any successful kill rate, the bottom hole pressure prediction must be greater than the sand face pressure for any reservoir fluid flow rate. In graphical terms, the wellbore hydraulics curve must lie above or tangent to the inflow performance relationship. Kouba \textit{et al} built the wellbore hydraulics performance curves for various combinations of injection and blowout rates by adding pressure losses resulting from hydrostatic head, friction and acceleration to the outlet pressure. It is mathematically represented by
Friction losses are included in the resistance coefficient, $K$. Kouba et al consider that homogeneous flow is very likely in high flow rates. This method was employed to calculate the minimum flow rate to achieve a kill in Indonesia’s Arun blowout. The kill rate and density given by the method was accurate and essentially the same reported by Blount et al.\(^3\)\(^2\).

**Bottomhole Pressure Match Solution (Lower Limit)**

The authors proposed this solution to determine the liquid injection rate necessary to keep the bottomhole pressure equal to the reservoir pressure once the well has been killed. They substituted the reservoir pressure $p_R$ for flowing bottomhole pressure $p_{wf}$ in Equation 2.14, removed the acceleration pressure drop term, and solved for kill flow rate $q_{kfr}$. The resulting equation was:

$$q_{kfr} = A_{uw} \left\{ \frac{1}{144} \left[ p_R - p_o - \rho_{kfr} D_f \right] \frac{2 g_c}{K p_{kfr}} \right\}$$ \hspace{1cm} (2.15)

Equation 2.15 gives the necessary condition for determining the minimum kill rate; it is insufficient to guarantee that this rate will actually kill the well.

**Zero Derivative Solution (Upper Limit)**

Kouba et al designed this solution to seek the kill rate for which the wellbore hydraulics performance curve passes through a pressure minimum as the formation rate approaches zero. A vanishing or zero derivative of bottomhole pressure with respect to formation fluid rate is therefore the criterion for this solution. In order to accomplish this, they derived Equation 2.14 with respect to
the formation fluid rate and neglected the acceleration term. After applying the zero derivative condition \( q_g \rightarrow 0 \), the following equation was obtained.

\[
q_{kf} = \left( \frac{(\rho_{kf} - \rho_g) \; 2g \cdot c \cdot A_{in} \cdot D \cdot V}{(\rho_{kf} + \rho_g) \; K} \right)^{1/2}
\]  

(2.16)

The authors suppose that the zero derivative technique ensures that there is, at most, one intersection between the wellbore hydraulics performance and the reservoir performance curves for any kill rate greater than or equal to the zero derivative kill rate. Furthermore, if the zero derivative kill rate is less than the lower limit rate necessary to sustain the kill, then the lower limit rate is also sufficient to kill the well.

Kouba et al also presented an approach to estimate the liquid accumulation in the lower part of the well during an off-bottom dynamic kill. It depends on calculating the formation fluid flow rates below which a minimum value of liquid holdup can be established. The authors utilized Taitel, Barnea and Dukler’s mechanistic model to perform this method. They also used the Turner et al equation to obtain the minimum gas velocity required to suspend a liquid droplet, which is given by

\[
v_{crit} = 1.593 \left[ \frac{\sigma(\rho_{kf} - \rho_g)}{\rho_g^2} \right]^{1/4}
\]  

(2.17)

Equation 2.17 was rewritten in terms of standard volumetric flow rate to give the minimum gas rate to suspend a droplet.

\[
q_{crit} = 4.87 \frac{A_p \cdot p}{z \cdot T} \left[ \frac{\sigma(\rho_{kf} - \rho_g)}{\rho_g^2} \right]^{1/4}
\]  

(2.18)
When the gas flow rate is lower than the one calculated with the above Equation, the injected liquid will start to fall generating a liquid accumulation between the injection point and the bottom of the well. They considered that the minimum liquid fraction required to form slug flow is about 0.25 and that the transition from slug to bubbly flow is given when the liquid accumulation reaches 0.75. Therefore, liquid accumulation could be conservatively estimated as these values for each of these flow regimes.

Gillespie\textsuperscript{52} and Kouba's\textsuperscript{33} models do not present a way to estimate the required pumping time or kill fluid volume to fill up the section from the point of injection to the bottom of the hole. In other words, it is not possible to predict when the kill operation should stop with this method.

\textbf{Dhafer A. Al-Shehri (1994)\textsuperscript{53}}

Al-Shehri developed a dynamic kill computer program based on steady state system analysis for controlling surface blowouts of oil and gas. The model simulates multiphase flow with the aid of the Beggs and Brill correlation in blowout and relief wells, and predicts and links the expected reservoir performance with wellbore hydraulics. This can be used to design a kill operation by studying the effects of various injection rates, injection location, and the type of kill fluid on the flow behavior of blowing wells.

The procedure also considers an off-bottom kill application, and proposes the momentum kill concept and off-bottom dynamic kill as alternatives. The dynamic kill assumes that only formation fluid exists below the point of injection.

The model was successfully tested for an on-bottom dynamic kill with data from the Indonesia's Arun blowout. The calculated kill parameters agree very well with the values reported by Kouba\textsuperscript{33} and Blount\textsuperscript{32}. 
Oudeman et al designed, executed and analyzed a full-scale field test to study how a dynamic kill proceeds in a high rate gas well. They utilized a producing well with 5.5" tubing and 1.75" coiled tubing with a down hole pressure gauge to inject the brine control fluid. Several tests were carried out at different flow conditions. After analyzing the test results, the authors proposed equations to predict the following kill parameters for a successful and efficient kill job.

**Pump rate**

The authors propose that six parameters determine the minimum rate to kill the well. These parameters are the flow resistance of the blowout well, reservoir pressure, surface pressure, depth of interception (between kill and formation fluid), kill fluid density and average well effluent density. Their equation to obtain the pump rate is given by.

\[
q_{kf} = \frac{1}{R} \left[ \frac{p_r - p_s}{2gL} - \frac{\rho_g \sqrt{gL}}{\rho_{kf} - \rho_g} \right] \frac{1}{\rho_{kf} - \rho_g}
\]

Where, \( q_{kf} \) is the kill flow rate \((m^3/s)\), \( R \) represents the flow resistance \((m^{-4})\), \( p_r \) reservoir pressure \((kg/m\cdot s^2)\), \( p_s \) surface pressure \((kg/m\cdot s^2)\), \( g \) gravitational acceleration \((m/s^2)\), \( L \) true vertical depth of intersection \((m)\), \( \rho_g \) average gas density between the flowing bottomhole conditions and surface conditions \((kg/m^3)\), and \( \rho_{kf} \) is kill fluid density \((kg/m^3)\).

Oudeman et al obtained excellent results with the homogeneous flow model. They observed that at the high flow rates encountered in the blowing well, slip between gas and liquid do not play an essential role, and refined multiphase flow models did not yield answers significantly different from homogeneous one.
Pump time

The authors' experience obtained during the field tests to study hydraulic well killing indicated that the well is killed once a sufficient volume of fluid has been pumped to create a column to balance the reservoir pressure. Hence, they proposed the following equation to calculate the kill time.

\[ t_k = \frac{A(p_R - p_s)}{q_{sf} g \rho_{sf}} \]  

(2.20)

Where, \( t_k \) is the time to kill the well (s), and \( A \) represents the area of the blowout conduit (m\(^2\)). The authors pointed out that Equation 2.20 may not be applicable when the formation pressure has to be balanced partially by the friction pressure drop of the kill fluid.

Kill volume

Oudeman et al\(^{54}\) suggested one extra well volume be pumped to sweep the well clean, therefore the required mud volume can be calculated by

\[ V_{sf} = q_{sf} t_k + V_{well} \]  

(2.21)

Where, \( V_{sf} \) is the volume of the kill fluid and \( V_{well} \) is the volume of the well (m\(^3\)).

Carlos Osornio, Humberto Castro, Victor Vallejo, and Enrique Ayala (2001)\(^{55}\)

The authors used Mexico's Cantarell field blowout to analyze, calculate, and compare the kill parameters that obtained from the momentum and dynamic kill methods. Those methods are the only ones available in the oil industry to control blowouts by pumping kill fluid through a string in a well.

The off-shore gas blowout occurred in the biggest oil field in Mexico, which is located in the Campeche Bay of the Gulf of Mexico. The drilling rig
caught fire burning approximately 230 MMscfd. The gas flow rate was calculated solving simultaneously the Forcheimer and Cullender and Smith  equation. Considering seawater as control fluid, the momentum kill study gave a kill flow rate about three times greater than dynamic kill. The well was controlled with a pump rate practically equal to that given by the dynamic kill method.

The authors conclude that the dynamic kill concept was a useful and appropriate method to analyze and understand what happened during the control, since the calculated and the real kill rate agreed very well. Another conclusion from this study was that the assumption of a homogeneous flow at high flow rates gave very good results.

2.3 Unsteady State Flow Models

Santos and Bourgoyne developed a simulator to predict loads imposed on the diverter system and pressure peaks occurring during the well unloading following an on-bottom shallow gas blowout. The study was conducted to improve the design criteria and operating practices of the diverter system to make their usage safer and more reliable during shallow blowouts. The motivation was that the peak of pressure that occurs when the gas reaches the surface has generated several failures of diverter equipment, leading to blowouts.

They built a mathematical model based on the simultaneous solution of five equations: the continuity equation, the momentum balance equation, an equation of state for the gas, a semi-empirical relationship between the gas and liquid in-situ velocities, and a gas reservoir model.

The authors verified the model with data from experiments conducted at the LSU Petroleum Engineering Research and Technology Transfer Laboratory with a full scale well connected to a 6-inch vent line. A variety of sensors were placed to measure and record several important functions during the well
unloading process. Four drilling fluids with different properties were used during the experiments.

Santos analyzed the diverter operations from some shallow gas drilling environments utilizing the results given by the model and reached the following conclusions. For most of the computer runs, the maximum pressure at the casing shoe occurred when the gas reaches that point. Small diverter line diameters resulted in high maximum wellhead pressure and high upward loads on the upper portion of the well.

They also found out that the pressure peaks are caused by the fast increase in velocity of the liquid flowing ahead of the two-phase mixture when the gas approaches the surface. Hence, they recommend that the diverter system components should be designed to withstand pressure as high as 1000 psi.


Starrett et al developed a computer simulator of the flow and pressure behavior in wellbores and diverters to predict performance during on-bottom shallow gas blowouts. The authors considered four main zones: the reservoir, the two-phase liquid/gas region in the wellbore, the liquid being displaced ahead of the two-phase region, and the diverter piping.

The authors performed a simulation, and for the conditions simulated, they found out that the pressure and velocity distributions were very responsive to changes in bottom hole pressure, diverter diameter, and wellbore diameter, but relatively insensitive to changes in initial circulation rate. Furthermore, they conclude that the pressure and velocity behaviors depend strongly on the initial differential between bottom hole pressure and reservoir pressure, and on the wellbore and diverter diameters as determined by Santos et al.

♦ Michael Wessel, and Brian Tarr (1991)

Wessel and Tarr developed a method to control underground blowouts based on the dynamic kill concept. The procedure proposes a set of equations to
determine the pump rate to stop the flow with either an infinite volume of kill mud or when the first kill mud reaches the fractured formation. The derivations assumed homogeneous multi-phase flow.

They also derived an equation to estimate the time and kill mud volume required for controlling the well for any given kill mud density/pump rate combination.

**Pump rate for infinite volume**

The authors defined this kill rate as the minimum injection rate that will ever stop the flow. It can be calculated by

\[
q_{k\infty} = J \left\{ \left( p_F - p_R + \frac{2 \rho_{kj} E}{\rho_g} - E \right) - 2 \left( \frac{\rho_{kj} E}{\rho_g} + p_F - p_R \right) \left( \frac{\rho_{kj} E}{\rho_g} - E \right) \right\} \tag{2.22}
\]

Where:

\[
E = \frac{V_s \rho_g \cos \phi}{A_{an}} \tag{2.23}
\]

The advantage of defining this rate is the possibility that it may be achieved with the rig equipment. However, an infinite or very large volume of kill fluid may be needed.

**Pump rate for minimum volume**

Wessel and Tarr determined that this is the kill rate required to control the well as soon as the first control fluid reaches the fractured formation.

\[
q_{kOH} = \frac{J(E + p_F - p_R)^2}{2 \left( \frac{\rho_{kj} E}{\rho_g} + p_F - p_R \right)} \tag{2.24}
\]

Here \( E \) is defined by Equation 2.23.
Injection rates given by Equation 2.24 are usually high. Those high flow rate requirements may not be achievable with available rig equipment, and additional pumping units would be required. However, any combination between Equations 2.22 and 2.24 would fulfill the requirements to kill the flow.

The authors also derived a method for determining the time and therefore the kill mud volume to stop the underground flow and kill the well. It was based in numerical integration of the equations that predict the rate of influx from the formation and bottomhole pressure. They suggest that an estimate of the total kill mud volume required is the volume pumped during the time required to stop formation flow plus one annular volume. Once a kill pump rate and mud weight are selected, these calculations can be made. The required mud volume should be built before beginning the kill in order to execute the kill procedure without interruptions.

Wessel and Tarr pointed out that the productivity index of a gas zone flowing underground is approximately proportional to the product of the formation's permeability and thickness. If this product is low, there is a good probability of stopping the flow with the available rig equipment, but the opportunity diminishes as formation productivity increases. Hence, by estimating the formation permeability and thickness for a potential zone to be drilled, you can determine whether an underground gas flow from the zone could be controlled with the available rig equipment or whether additional pumping units or relief well would be required.

Adam T. Bourgoyne Jr., David Barnett, and Dan Eby (1996)

Bourgoyne et al developed an advanced blowout control computer model. It includes a steady state calculation option for quickly estimating the minimum dynamic kill rate for a given kill fluid and well geometry. It also contains an unsteady state flow option to estimate the volume of kill fluid needed and to estimate a predicted pressure schedule during dynamic kill operations.
The authors used a modular approach to develop the model that provides flexibility to simulate flow through the diverter system, surface blowouts and underground blowouts that can be controlled with either an internal injection string or one or more relief wells. They also included a flow section to allow the analysis for flow through either a pipe or an annulus with alternative methods commonly used for determining equivalent annular diameter. A flowing formation model was coupled to wellbore system to compute the formation flow rate under blowout conditions as well as formation fluid influx and bottomhole conditions during the control.

The authors chose Excel 5.0 as the spreadsheet program to be used for the application framework. They utilized subroutines to perform the more complex calculations, which were written in Visual Basic.

* Fan Jun, Shi Tai-He, and Lian Zhang-Gui (1998)*

Fan Jun *et al* developed a dynamic kill model. It is capable of simulating the complete blowout process giving results for the fluid distribution, flow rate, fluid density, and pressure profile along the wellbore versus time. The model was developed for gas blowouts and assumes that the drill string is placed at the bottom of the hole during the complete blowout kill process.

The authors considered nine basic variables to describe the gas-liquid flow system: gas and mud density, gas and mud velocity, gas volume fraction, wellbore geometry, deviation angle, pressure and temperature. They adopted homogeneous flow model in the wellbore, since the co-current flow system is of rather high flow rate at the major stages in the kill process, which has been proven accurate enough to characterize the flowing nature in the mist flow regime.

Fan Jun *et al* included a gas reservoir model, which considers a non-Darcy term due to the high flow velocity around the borehole. Then the wellbore and reservoir mathematical models were linked, since any changes and
variations of the system performance in wellbore inevitably causes a response in
gas influx rate.

♦ O. L. A. Santos (2001)

Santos developed a mathematical procedure to calculate the kill parameters for a sea floor gas blowout. The procedure was based on the concept of an on-bottom dynamic kill. The computer program also predicts the time required to unload a deepwater well after its control has been lost, the gas production rate, the total volume of gas produced during the blowout, and the time and seawater injection rate required to dynamically kill the blowout.

The author coupled a wellbore model that predicts wellbore pressures to a gas reservoir model that calculates gas flow rates entering the well during the unloading part of the process and during the blowout itself. Santos established the top end of the wellbore model at the sea floor as a boundary condition, which is controlled by the hydrostatic pressure generated by the seawater. Hence, this boundary condition value depends directly on water depth. He also considered in his procedure both surface control by pumping kill fluid through an injection string and control through a relief well.

Santos performed several simulation runs to analyze the effect of some drilling variables, reservoir properties, and the effect of high backpressure generated by seawater hydrostatic head on blowout flow rates and kill parameters for a hypothetical deepwater scenario. Santos concluded that the greater the well diameter, the greater both the gas flow and the required kill fluid injection rate will be, since higher wellbore diameter provides smaller frictional pressure losses. On the other hand, the increase in water depth results in lower gas production rate due to seawater hydrostatic pressure at the wellhead.

The author also recommends that under no circumstances should an ultra deepwater blowout be controlled using the surface diverter system. With flow to the seafloor, the seawater backpressure restricts the blowout gas flow rate, and that hydrostatic pressure will be lost if the diverter is employed since the riser will
be filled with gas after its unloading. Hence, if a gas kick is taken in an ultra deep-water situation, the blowout preventers should be closed or the marine riser disconnected. Simulation results showed that the riser can collapse at its bottom due to the high differential pressure. He also pointed out that if the diverter system is used, the very high gas flow rate can erode the equipment and the presence of inflammable and explosive fluids on board can provoke disastrous accidents.
CHAPTER 3

CURRENT ENGINEERING PROCEDURES FOR OFF-BOTTOM BLOWOUT CONTROL

Dynamic kill and momentum kill are currently the only two engineering procedures that can be employed to analyze, design, and calculate the kill parameters required to control an off-bottom blowout by pumping a fluid through an internal injection string that conducts the kill mud into the wellbore. Both methods have been used in field applications and have been reported to be successful for controlling blowouts. The following section presents a study performed to evaluate these concepts.

3.1 Dynamic Kill

Dynamic kill is a relatively new technique. It was developed by Mobil Oil Corporation and was first reported by Blount and Soeinnah. The method was designed to control Indonesia's Arun field blowout. The well caught fire in June 1978, destroying the drilling rig and burning for 89 days at an approximate rate of 400 MMscfd. Due to the well's high deliverability and potential, it was expected to be an extremely difficult well to kill. However, the engineering procedure was so successful that the well was controlled one hour and 50 minutes after the kill started.

3.1.1 Concept

The dynamic kill method to control blowouts uses fluid pumped from the surface to a point downhole where it enters the blowout flow path to increase the frictional pressure drop and the hydrostatic pressure over the length of the blowout flow path. To obtain a successful kill, the summation of the frictional pressure losses and the hydrostatic pressure due to fluid densities must be greater than the formation pressure.
This concept can be better explained with Figure 3.1, which illustrates a well and its pressure gradient. Section (a) shows the well with mud in static conditions, with a hydrostatic pressure value at the bottom. In section (b), the drilling mud is pumped through the injection string, and as shown by the shaded area, the frictional pressure losses due to flow is used to increase the bottom hole pressure. In a kill operation, that pressure increment will help to stop the flow from the reservoir. However, it is important to avoid fracture of the open hole formations, since if the formation breaks down part of the kill fluid will go into the fracture, reducing the kill flow rate in the wellbore, and consequently the friction losses. Thus the advantage of killing the well dynamically will be notably reduced.

![Figure 3.1 Effect of frictional pressure losses on bottom hole pressure](image)

(Figure continued)
The main objective of the dynamic kill calculation technique is to determine the minimum injection rate of available kill fluid necessary to stop reservoir fluid flow into the wellbore (Kouba\textsuperscript{33}). The method is designed to kill the well by exceeding the natural flow capacity of the wellbore.

This technique is based on the steady state system analysis approach, which consists of a study between the reservoir inflow performance and the wellbore performance. System analysis, also known as NODAL analysis, has been used in production wells and has received widespread acceptance in the oil industry. Another successful application is in blowout control studies, since a well under blowout conditions is very similar to a production well, with the difference that the producing well is flowing under control and the reservoir fluids flow to the production facilities rather than to the atmosphere.
Figure 3.2 illustrates a blowout scenario. It can be seen that the reservoir and the wellbore can act as a single hydraulic system and that the whole system is affected by several factors such as reservoir pressure and properties, formation fluid characteristics, and wellbore and drillstring geometry.

From Figure 3.2 it can be seen that the system has two important components: the reservoir and the wellbore. The flow from the reservoir into the well has been called "inflow performance," and a plot of producing rate versus flowing bottomhole pressure is called an "inflow performance relationship" (Beggs60). On the other hand, the "wellbore hydraulics performance" is given by the flow behavior from the bottom of the well to the surface. Both inflow and wellbore performance can be mathematically represented, and the simultaneous solution of those analytical representations will give the relationship between the
formation flow rate and the pressure drop for a specific spot. In the blowout control area, that spot is typically selected as the bottom of the well. Hence when the wellbore performance curve is above the inflow performance, the bottomhole pressure is greater than the formation pressure and the reservoir no longer produces.

### 3.1.2 Mathematical Model and Methodology

The inflow performance and wellbore hydraulics relationships will interact to determine the conditions at which the dynamic kill will be achieved. Hence, the following section will present a procedure applying this concept to determine the required kill parameters for a gas blowout. The gas case was selected because about 90% of all blowouts involve gas as reported in Chapter 2. The required kill parameters include.

- Gas flow rate under blowout conditions
- Pressure profile in the system under blowout conditions
- Kill fluid density
- Kill fluid injection rate
- Pressure profile in the system at the beginning of the control and after formation fluid influx stops
- Surface pump pressure
- Hydraulic horsepower

The required steps to design and compute the above kill parameters utilizing the steady state system analysis approach are the following:

1. Compute the inflow performance relationship (IPR) for the reservoir and plot it as function of flowing bottom hole pressure versus gas flow rate. Determination of the inflow performance needs a connection between formation fluid flow rate and the sand face pressure, and that relationship is given by a reservoir model such as Equation 4.43. The IPR is built assuming different gas flow rates and solving the equation for the bottomhole flowing pressure.
2. Compute the wellbore hydraulics performance curve and plot it as function of flowing bottom hole pressure versus gas flow rate superimposed on the plot of the IPR. Again determining the wellbore performance requires a relationship between formation fluid flow rate and the bottom hole pressure, which is given by the Cullender and Smith model, Equation 4.44. The wellbore hydraulic performance is completed assuming different gas flow rates and solving the equation at the sand face. Figure 3.3 displays a typical behavior of the system analysis. The IPR curve shows the performance of the reservoir, and the WHP curve represents the performance of the wellbore when flowing only gas, in other words the pressures required to move the resulting rates of gas through the wellbore system to the atmosphere.

3. Determine the gas flow rate under blowout conditions, which is given by the intersection of the inflow performance curve "IPR" and the wellbore hydraulics performance curve "WHP" on Figure 3.3. This situation indicates that the well has been completely unloaded of all liquid, except any that is flowing from the formation, and a free flowing equilibrium condition has been reached.
4. Plot the pressure profile in the well under blowout conditions utilizing the gas flow rate obtained in the previous step and Equation 4.44. This equation is solved for small depth increments in the wellbore.

5. Compute the wellbore hydraulics performance curve for each of various kill fluid injection rates with one selected kill fluid density in combination with a range of gas flow rates up to blowout flow rate, then plot them on the graph accomplished in step 2. These curves are calculated taking into account pressure changes due to elevation, friction, and acceleration of the mixture. They are obtained utilizing Equation 4.29 and the respective fluid property correlations given in Chapter 4. Figure 3.4 illustrates the wellbore hydraulics performance curves for different injection rates. Analyzing one of these lines, it can be seen that as the gas flow rate increases from zero, the bottom hole pressure typically decreases due to reduction in hydrostatic pressure. This portion of the curve shown as a dashed line is referred to as being hydrostatically dominated. On the other hand, further increases in the gas flow rate eventually increase the bottom hole pressure due to increasing frictional pressure losses. Consequently, this segment of the curve shown as a solid line is known as friction dominated.

6. Select the kill injection rate from the plot as the line of constant injection rate, which is just above or tangent to the inflow performance relationship curve. Therefore, injection rate #3 on Figure 3.4 is the lowest rate that will achieve a kill. At that kill fluid rate, a stable gas lift flow condition would not be possible, and the well would be killed. On the other hand, if the wellbore hydraulics performance intersects the reservoir performance curve, as for injection rate #2, then a stable flow condition would result. That is, the reservoir would continue to produce at the rate corresponding to the point of intersection, and the well would not be killed.
7. If the selected kill injection rate is too high to handle with the available pumping equipment, repeat steps 5 and 6 with a higher kill density. Otherwise, proceed with step 8.

8. Plot the pressure profile in the system as a function of depth for the selected kill injection rate and density. This will give a good approximation of the pressure conditions in the wellbore just after the formation fluid influx stops. Hence those pressures can be compared with the burst ratings of the wellbore tubulars and the fracture pressure in the open hole interval.

9. Estimate the frictional pressure losses and the hydrostatic pressure in the injection string utilizing Equations 4.62 and 4.63 respectively as well as the selected kill flow rate and kill fluid density.

10. Calculate the surface injection pressure employing the frictional pressure losses and the hydrostatic pressure previously calculated and Equation 4.61.
11. Determine the hydraulic horsepower requirement using the surface injection pressure from the previous step.

This procedure is represented by the flow chart in Figure 3.5, which shows the algorithm utilized to estimate the kill parameters applying this theory.

A real blowout control calculation presented in the next section will be used to explain this procedure in detail.

Some blowouts necessitate very high pump pressure and horsepower to be controlled, which is not always possible with the equipment available on the site. Nevertheless, those parameters can be reduced by use of special drag reducing fluid additives. If a friction reducer is present in the kill fluid, it should be taken into account to calculate the frictional losses in the system. But if the pump pressure and horsepower cannot be reduced to acceptable limits, either additional pumping units or a relief well will be needed.

3.1.3 Computer Program

One of the aims of this research was to investigate how the current blowout control methods perform at off-bottom conditions, as well as describe their deficiencies and limitations. In order to achieve this goal, a computer program is desirable to perform calculations to analyze several blowout control scenarios.

Therefore, a dynamic kill computer program following the previous procedure was created to accomplish the analysis. It is important to point out that the program was based on the conventional dynamic method, which assumes that only formation fluid is present below the injection point. This consideration is contemplated in nearly all current published models, and most consider just the hydrostatic head of the fluid. In this program all the components of the pressure gradient equation are considered (hydrostatic head, friction losses, and acceleration).
Figure 3.5 Algorithm to estimate the dynamic kill parameters
(Figure continued)
Once the computer program was finished, it was compared to previously published examples to evaluate its performance. The calibration was carried out using field data and results from other models published in the literature. \(^{32, 33, 53}\)

**Table 3.1** Blowout data from Mobil Oil Indonesia’s Arun field well No. C-II-2\(^{32}\)

<table>
<thead>
<tr>
<th>Input Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir pressure (psia)</td>
<td>7,100</td>
</tr>
<tr>
<td>Reservoir temperature (°F)</td>
<td>230</td>
</tr>
<tr>
<td>Gas specific gravity</td>
<td>0.6</td>
</tr>
<tr>
<td>Casing ID (in)</td>
<td>8.535</td>
</tr>
<tr>
<td>Drillpipe OD (in)</td>
<td>5.00</td>
</tr>
<tr>
<td>Drillpipe ID (in)</td>
<td>4.275</td>
</tr>
<tr>
<td>Pipe roughness (in)</td>
<td>0.0018</td>
</tr>
<tr>
<td>Measured depth (ft)</td>
<td>10,210</td>
</tr>
<tr>
<td>True vertical depth (ft)</td>
<td>9,650</td>
</tr>
</tbody>
</table>

**Solution is reached and the kill parameters are predicted**

**A**

Modify string depth or obtain another pumping system. Otherwise consider another control technique (capping, relief well)

**B**

Determine the frictional pressure losses in the injection string

Calculate the surface injection pressure

Determine the hydraulic horsepower

Does the pumping system meet the required hydraulic horsepower

Yes

No
The program was run with data from the blowout that occurred in Mobil Oil Indonesia's Arun field well No. C-II-2.\textsuperscript{32} It is considered the largest gas blowout ever.\textsuperscript{53} The results were compared with previously published models that used this information to calculate the kill parameters. Data were extracted from references 32, 33, and 53. Table 3.1 presents the blowout information.

Figure 3.6 shows the reservoir inflow performance and wellbore hydraulics performance curves for different injection rates that were calculated and generated with the model built in this work and input data from the Arun blowout.

![Bottomhole Flowing Pressure vs Gas Flow Rate](image)

**Fig. 3.6 Predicted kill flow rate for Arun blowout.**
Analysis of the results of the Arun blowout calculation, see Figure 3.6, showed the following. The inflow performance curve "IPR" shows the performance of the reservoir. The "0 bpm" curve represents the wellbore performance of the system when only gas is flowing. The intersection of the "IPR" curve and "0 bpm" curve corresponds to the well condition after all of the liquid has been unloaded from the wellbore and free flowing equilibrium condition has been reached. According to the calculations given by the program, the Arun field's well No. C-II-2 was producing at an approximate rate of 380 MMscfd during the blowout, with a bottom hole pressure around 6,000 psi.

Figure 3.6 also shows an injection of water at a rate of 20 bpm down the drillpipe would result in a stable flow condition. That is, the reservoir would continue to produce at a gas flow rate of about 310 MMscfd and a bottom hole pressure around 6,400 psi. A stable flow condition would also result for an injection rate of 40 bpm with a producing rate and bottom hole pressure of 205 MMscfd and 6,600 psi respectively. As can be seen from this system analysis approach, it is expected that the well passes through a series of flowing conditions during the control due to kill fluid entering the annulus.

In achieving a dynamic kill of the Arun blowout, the calculations indicate that a water injection rate of approximately 83 bpm would give a bottom hole pressure of 7,100 psi, which would be enough to create sufficient backpressure at the formation face to prevent further gas flow from the reservoir.

The solutions for the Arun blowout given by others' dynamic kill models are presented in Table 3.2. It can be seen in that the dynamic kill computer program developed in this work has excellent agreement with other models. It may therefore be used with confidence to perform the sensitivity analysis for different blowout scenarios and detect the reach and limitations of the dynamic kill method during blowout control operations with the injection string at off-bottom conditions.
Table 3.2. Results from different dynamic models for Arun gas blowout.

<table>
<thead>
<tr>
<th>Model</th>
<th>Gas flow rate (Mscf/D)</th>
<th>Kill flow rate (bpm)</th>
<th>Kill fluid density (ppg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blount and Soeiinah</td>
<td>360,000</td>
<td>80</td>
<td>8.33</td>
</tr>
<tr>
<td>Kouba</td>
<td>370,000</td>
<td>84</td>
<td>8.33</td>
</tr>
<tr>
<td>Dhafer Al-Shehri</td>
<td>447,000</td>
<td>82</td>
<td>8.33</td>
</tr>
<tr>
<td>Computer Program</td>
<td>380,000</td>
<td>83</td>
<td>8.33</td>
</tr>
</tbody>
</table>

3.1.4 Application to and Limitations for Off - Bottom Conditions

The review of the Arun blowout is an example that shows that the dynamic kill technique performs very well when the injection string is near or on - bottom. However, there are additional complications when this method is applied in off - bottom conditions.

Bourgoyne\textsuperscript{62}, Gillespie\textsuperscript{52} and Kouba\textsuperscript{33} have explained the concept and methodology for applying the dynamic method in off - bottom conditions. In addition, the conventional dynamic kill, which considers only formation fluid below the injection point, has been successfully applied to control several off - bottom blowouts.

In this research, a study was undertaken to investigate the conventional dynamic kill method. It was carried out by analyzing different blowout scenarios, reviewing real blowout control operations from the literature as described later in this chapter and Chapter 5, and analyzing the dynamic kill concept at off - bottom circumstances. The following are the results.

- The conventional dynamic kill method does not take into account that the kill fluid may fill the wellbore from the injection point to the bottom of the well, so the most common, conservative assumption is that only formation gas remains in that part of the wellbore during the control. Hence, conservative decisions would call for a mud density from the injection depth to the surface sufficient to balance the formation pressure in static conditions. This may be
impossible to achieve when the formation pressure is high and the length
between the surface and the injection depth is short, see Figure 3.7. Due to
this fact, the opportunity to develop an in-well control would be discarded,
and another more expensive and time consuming blowout control
methodology such as snubbing in or relief well would be considered.

Figure 3.7 Effect of short injection string on dynamic kill

- The dynamic kill method is not guaranteed to displace, or remove completely,
  the formation fluid from the injection point to the bottom of the well. Its design
  considers stopping the flow with bottomhole pressure just reaching the
  formation pressure. Therefore, the pressure is inadequate to force the kill fluid
to flow from the injection point down into the producing zone. If the injection
string depth is distant from the bottom in an authentic off-bottom scenario, a
considerable amount of gas may remain in the section below the injection
point. If the circulation rate is reduced or stopped, it may start to migrate,
expanding, and forcing some drilling fluid out of the well. Consequently, the average density will be reduced in the system, and the well may begin to unload again. Figure 3.8 illustrates this event.

![Diagram of wellbore and kill mud](Image)

*Figure 3.8. The well may unload if a considerable amount of gas remains in the wellbore*

- The dynamic kill is based on the steady state system analysis approach\(^5\), and it was earlier shown that the system analysis is a relationship between the reservoir inflow performance and the wellbore hydraulic performance. For blowout control applications, performance is plotted on a bottom hole pressure versus gas flow rate graph such as Figure 3.2. If an off-bottom condition is presented this approach cannot be precisely employed to analyze and compute the kill parameters because of the uncertainty about the real conditions and mixture properties below the injection depth. Consequently,
the pressure gradient cannot be accurately known between the injection depth and the formation depth. As a result, the wellbore hydraulic performance curves cannot be accurately determined. This scenario is schematically illustrated in Figure 3.9.

![Figure 3.9 Effect of utilizing system analysis approach in off-bottom scenarios](image)

Another disadvantage of the dynamic kill is that its design sometimes uses a fluid to control the well dynamically that is less dense than the fluid needed for a hydrostatic kill. The fluid would then have to be changed for a heavier one to maintain control in static conditions. Consequently, additional operations have to be planned and implemented properly to get a final control. This increases the complexity and risk of mistakes in conducting the kill.
The current off-bottom dynamic kill methods described by Gillespie and in more detail by Kouba provide means for predicting wellbore hydraulic performance below the injection point. However, they do not present a procedure for knowing when the lower wellbore section below the injection depth is completely filled with kill mud. The volume that must be pumped to make sure that the lower zone is completely full and the kill operation completed is unknown.

### 3.2 Momentum Kill

The momentum kill is a procedure based on fluid dynamics and was first reported in 1977 as a method that can be utilized to control off-bottom blowouts without tripping in to the bottom of the well. Grace and Watson have described the concept and mathematical model of this procedure as an alternative solution for off-bottom blowouts. Grace has also described successful control of blowouts by applying this technique.

#### 3.2.1 Concept

The momentum kill is based on the concept that when two fluids traveling in opposite directions collide, the one with greater momentum controls the direction of flow for both. Therefore, in the blowout control operation proposed by these authors, the formation fluid and the kill fluid collide at the injection string depth. Conceptually, the momentum of the control fluid must be greater than the momentum of the formation fluid to stop the blowout fluid and force it back into the formation and to bring the well under control. This concept is schematically illustrated in Figure 3.10

This procedure uses the kill fluid velocity and density to generate a greater momentum than that of the formation fluid flow. Therefore, either high pump rates or kill densities are expected when this technique is utilized to design a blowout control. Consequently, a detailed analysis should be performed on the tubulars in the well and on the open hole in order to guarantee that they can contain the pressures during the control operation.
Applying this concept, the kill density employed to control the well should generate enough hydrostatic pressure to control the formation pressure in static conditions. Once the pump stops, the momentum of the kill fluid becomes nothing and the only way to keep the well under control is by utilizing the hydrostatic pressure of the drilling mud.

### 3.2.2 Mathematical Model and Methodology

The mathematical model of momentum kill is based on the Newton’s Second Law of Motion\textsuperscript{16}, which states that the net force acting on a system is equal to the rate of change of momentum of that system. Only forces acting at the boundaries of a prescribed space are concerned: any force within the space is involved only as one half of an "action - and - reaction" pair and so does not
affect the overall motion behavior. Mass conservation and real gas laws are utilized to derive the equations that constitute the analytical model.

The engineering design procedure of momentum kill is essentially composed of two equations. One calculates the momentum of the gas flowing up, and the other for computes the momentum of the kill fluid being pumped down. They are respectively given by

\[ M_g = 0.0115 \frac{\rho_{gsc} q_{gsc}^2 z_n T_n}{\gamma_g P_n A} \]  

(3.1)

and

\[ M_{kf} = \frac{\rho_{kf} q_{lf}^2}{A g_c} \]  

(3.2)

A complete derivation of the above equations is presented in Appendix A. In each case, the area, \( A \), considered is that of the wellbore just below the injection point.

The following section will present a procedure applying this concept to determine the required kill parameters such as:

- Gas flow rate under blowout conditions
- Pressure profile in the system under blowout conditions
- Kill fluid density
- Kill fluid injection rate
- Surface pump pressure
- Hydraulic horsepower

Thus the required steps to design and compute the above kill parameters utilizing the momentum kill approach are the following:
1. Determine the gas flow rate and pressure profile in the system under blowout conditions, which is given by the procedure explained in the dynamic kill section 3.1.2 (steps 1 through 4).

2. Calculate the profile of the gas deviation factor in the system utilizing the Equation 4.24.

3. Compute the profile of the gas density in the system employing Equation 4.22.

4. Estimate the profile of the momentum of the gas with equation 3.1, and plot it versus depth.

5. Calculate the momentum of the kill fluid employing equation 3.2, for various kill fluid injection rates and kill densities that can be handled with the available pumping units. The selected densities should generate enough hydrostatic pressure to control the formation pressure in static conditions, but those hydrostatic columns should not reach the fracture pressure.

6. Superimpose the momentum of the kill fluid calculated in step 5 on the plot of step 4. Select the kill rate and density combination that matches or exceeds the momentum of the gas at the injection string depth.

7. If the selected kill injection rate is too high to handle with the available pumping equipment, repeat step 5 with a higher kill density.

This procedure is represented by the flow chart in Figure 3.11, which shows the algorithm utilized to estimate the kill parameters applying this theory.

3.2.3 Computer Program

A computer program was developed utilizing the momentum kill concept with the objective of developing a sensitivity analysis in order to know how this method performs under different blowout scenarios by changing parameters such as formation properties, reservoir fluid properties, formation fluid flow rate, wellbore and tubulars geometries, and injection depth.
Collect the blowout data

Determine the reservoir and fluid properties

Compute the IPR

Compute the WHP when only gas is flowing

Determine the gas flow rate and FBHP, and plot pressure profile

Estimate the profile of the gas deviation factor

Compute the profile of the gas density

Determine the momentum of the gas and plot it versus depth

Select a kill flow rate and density

Calculate the momentum of the kill fluid and plot it on previous graph

Is the momentum of the kill fluid greater than the momentum of the formation fluid?

Yes

Required kill flow rate and density are obtained

No

Does the pumping system have capacity to pump the selected rate

Yes

Solution is reached and the kill parameters are predicted

No

Increase either kill flow rate or kill density

Increases string depth or obtain another pumping system. Otherwise consider another control technique (dynamic kill capping, relief well)

Figure 3.11 Algorithm to estimate the momentum kill parameters

The momentum kill program was based on the mathematical model and procedure previously presented. Once the computer program was finished, it was
validated, using field data and results published in the literature. Table 3.3 shows that the results from the momentum kill computer program developed in this work match with the published results. Therefore, it can be used to analyze additional blowout scenarios and to formulate conclusions about this method.

<table>
<thead>
<tr>
<th></th>
<th>Momentum of the gas</th>
<th>Momentum of the kill fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 ppg</td>
<td>20 ppg</td>
</tr>
<tr>
<td>Published Results</td>
<td>6.8 lbf</td>
<td>8.9 lbf</td>
</tr>
<tr>
<td>Program Results</td>
<td>6.8 lbf</td>
<td>8.9 lbf</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.8lbf</td>
</tr>
</tbody>
</table>

### 3.2.4 Momentum Kill Analysis

An analysis was performed on momentum kill in order to determine its performance. The study concentrated mainly on the following elements.

- Careful derivation of momentum equations to give a logical analysis of the concept.
- An analytical study applying a pressure profile analysis and the critical velocity concept to investigate the flow direction after the collision between the kill fluid and the formation fluid.
- An analysis of the two published blowouts in the literature that used this concept to regain the control of the well in order to understand what actually controlled those wells. And calculate and compare the kill parameters for different blowout scenarios utilizing both the momentum and dynamic concept.

#### 3.2.4.1 Analytical Study

This part of the work presents an analytical study performed on the momentum kill concept. The study focused on two elements: an analysis of the derivation of the momentum equations used in the engineering design procedure
and an analysis of the flow direction after the collision between the formation fluid and kill fluid.

The engineering design procedure of the momentum kill concept is described as being based on Newton’s Second Law of Motion\(^{16}\), which is mathematically represented by

\[
\sum F_{\text{External}} = ma = \frac{d}{dt} \left( \frac{d(Momentum)}{dt} \right)
\]

(3.3)

Applying the control volume formulation to the linear momentum of the system\(^{17}\):

\[
\frac{d(Momentum)}{dt} = \int_{cv} (v \rho \nu) \cdot dA + \frac{\partial}{\partial t} \int_{cv} v \rho dV
\]

(3.4)

Combining Equation 3.3 and 3.4:

\[
\sum F_{\text{External}} = \int_{cv} (v \rho \nu) \cdot dA + \int_{cv} v \rho dV
\]

(3.5)

Where \( v \) represents the fluid velocity, \( \rho \) the fluid density, \( A \) the flow area and \( V \) is the volume in the control volume. Equation 3.5 is called the control volume formulation of Newton’s Second Law, also known as the linear momentum equation. It states that the summation of all external forces (body, normal, and frictional) on a system is equal to the rate of change of momentum of that system.

In a blowout scenario a reasonable consideration is that steady state has been reached after the well has been completely unloaded of all the mud and only formation fluid is flowing through the well. Thus, Eq. 3.5 becomes:

\[
\sum F_{\text{External}} = \int_{cs} (v \rho \nu) \cdot dA
\]

(3.6)
Considering intervals with constant area the above equation becomes:

\[ \sum F_{\text{External}} = \nu p v A \] \hspace{1cm} (3.7)

Replacing the velocities by \( \nu = q / A \) and introducing the constant of proportionality in Equation 3.7:

\[ \sum F_{\text{External}} = F_{\text{Momentum change}} = \frac{\rho_{sf} q_{Msf}^2}{g_c A} \] \hspace{1cm} (3.8)

Equation 3.8 is the relationship to compute the momentum force of an incompressible fluid, in this case kill mud. The equation to calculate the momentum force of a compressible fluid such as formation gas, is obtained if the principle of mass conservation and real gas law is applied to Equation 3.8, see Appendix A for the derivation, this is given by

\[ \sum F_{\text{External}} = F_{\text{Momentum change}} = \frac{\rho_{gsc} q_{gsc}^2 zRT}{\gamma g M_n p_n A g_c} \] \hspace{1cm} (3.9)

The procedure that the momentum kill method utilizes to calculate the kill rate and density combination is to require the momentum of the kill fluid (Eq. 3.8) to be equal to greater than the momentum of the formation gas (Eq. 3.9).

\[ \frac{\rho_{sf} q_{Msf}^2}{g_c A} \geq \frac{\rho_{gsc} q_{gsc}^2 z_n RT_n}{\gamma g M_n p_n A g_c} \]

Then, for a given kill density, the above equality is solved for the kill flow rate as follows:
However, the force term on the left hand side ($\sum F_{\text{External}}$) of Eq. 3.8 and 3.9, that is neglected by the published momentum design procedure, is the sum of all forces acting in the system

\[
\sum F_{\text{External}} = \sum F_p + \sum F_T + \sum F_B
\]  

(3.11)

Where $F_p$ is the normal force, and it is due to the pressure into the system. It is given by

\[
F_p = \int_{cs} p \, dA
\]

Where: $p = \text{Pressure}$  
$A = \text{Flow area}$

The tangential force ($F_T$) is due to the viscous shearing stress of the fluid over the wellbore and pipe wall. It is mathematically represented by

\[
F_T = \int_{cs} \tau \, d\Lambda
\]

Where: $\tau = \text{Shear stress}$  
$\Lambda = \text{Contact area}$

And finally $F_B$ is the body force, and it is due to the gravity force, which acts in the direction of the gravitational field. It is given by

\[
F_B = g \int_{cv} \rho \, dV
\]
Where: $g = \text{Acceleration of gravity}$

$\rho = \text{Fluid density}$

$V = \text{Volume of fluid}$

Hence

$$\int_{cs} v \rho \cdot dA = \int_{cs} p \ dA + \int \tau \ dA + g \int_{cv} \rho \ dV$$

The equality of the rate of change of momentum and the external forces (Newton's Second Law of Motion) gives the conservation of momentum equation\textsuperscript{34} for flow in a linear system. It is presented in pressure instead of force and for upward flow direction and pressure drop defined as positive when upstream pressure is greater than downstream pressure.

$$\frac{d}{dL} (\rho v^2) = \frac{dp}{dL} - \frac{\pi d}{A} - \rho g$$

The pressure gradient equation\textsuperscript{34} is obtained combining both the conservation of momentum and conservation of mass equations (see Appendix B), and is given by:

$$\Delta p = \Delta p_{\text{acceleration}} + \Delta p_{\text{friction}} + \Delta p_{\text{elevation}}$$

Therefore, the forces given by the Newton's Second Law of Motion become:

$$F_{\text{momentum change}} = F_{\text{normal}} + F_{\text{tangential}} + F_{\text{body}}$$

The fundamental concept of well control states that the bottomhole pressure must be greater than or at least equal to the formation pressure to stop the formation flow.
\[ \Delta p_{bh} \geq P_{formation} \quad \text{or for a surface blowout} \quad P_{surf} + \Delta p \geq P_{formation} \]

It can be seen that the momentum kill design concept presumes to reach the formation pressure and stop the flow by considering only the acceleration component of Newton’s second law of motion. Both the friction and elevation terms are neglected and it is well known that these components play a very important role in these scenarios since they almost always have the largest magnitude in a blowout control. Examples of the relative magnitudes of pressures, which cause these forces, are given in section 3.2.4.2. Therefore, if the procedure considers Newton's Second Law of Motion as its basic equation, the external forces must be considered.

Another analysis of this procedure was an investigation of the flow direction after the collision between the formation fluid and kill fluid. This investigation was based on the analytical work performed by Turner et al\textsuperscript{61}, Gillespie et al\textsuperscript{52}, and Kouba et al\textsuperscript{33}. They considered that liquid droplets entrained in a gas stream will be lifted out if the gas velocity is greater than the critical gas velocity. This concept was also, experimentally proved by Bourgoyne et al\textsuperscript{62} and Flores et al\textsuperscript{63}.

Therefore, this theory states that if the gas velocity at the injection string depth in the blowout well is greater than the critical gas velocity, the gas stream will lift out the kill fluid after the control operation begins. And as a result, the possibility of stopping the flow due to the collision between the formation and kill fluid and force the gas back into the formation will be minimal. The gas velocity, when only formation gas is flowing through the well, depends on reservoir and reservoir fluid properties as well as wellbore geometry. But just as soon as the control operations start, the conditions at the well (pressure profile, gas influx, fluid properties, etc) begin to change because of kill mud presence. As a consequence, the speed of the gas decreases to such level that the critical gas velocity may be reached and kill fluid may begin to fall below of the injection point.
However the momentum method does not consider that the conditions in the system are continuously changing, since its design calls for stopping the blowing fluid at the instant of collision. But it is expected that the formation gas is at its maximum velocity just before the impact or before the kill fluid begins to flow from the injection depth to the surface. This is because the bottom hole pressure is at a minimum value hence the gas flow rate reaches its maximum value. Thus the key factor to consider whether the kill fluid may be ejected by the gas stream is determined by critical gas velocity, which is the minimum velocity that will lift all liquid entering the flow path. It is a function of the size, shape, and density of the mud particle and density and viscosity of the gas medium. The critical gas velocity is estimated as follows.

Gillespie et al.\textsuperscript{52} presented a procedure to calculate the critical gas velocity. Their method considers two factors: the largest diameter of droplet likely to exist in the gas stream and a conservative value for the drag coefficient of the droplet. They used three approaches to estimate the maximum likely droplet size. In this analysis only two of them will be presented, those that presented the maximum and minimum critical velocity (in other words, the extreme cases). One of the approaches was elaborated by Karabelas; it is given by

\[ d_{\text{max}} \approx d_{95} = \frac{4d_i}{\left(\frac{d_i \rho_c v_c^2}{\sigma}\right)^{0.6}} \quad (3.12) \]

The other one was developed by Sleicher, it is calculated by

\[ d_{\text{max}} = \frac{38\sigma}{\rho_c v_c^2} \left[ \frac{g_c \sigma}{\mu_c v} \left[ 1 + 0.7 \left( \frac{\mu_d \sqrt{v}}{g_c \sigma} \right)^{0.7} \right] \right] \quad (3.13) \]

When the relative settling velocity of the largest droplet is just equal to or greater than the average gas velocity, the fluid will be able to fall below of the injection point. Otherwise, the gas will sweep all droplets out of the well.
The critical gas velocity or the settling velocity of a drop is obtained by

\[ v_{\text{crit}} = \sqrt{\frac{4gd_{\text{max}}(\rho_d - \rho_c)}{3\rho_c K_d}} \]  

(3.14)

In Equation 3.14, \( K_d \) represents the drag coefficient, which is function of the Reynolds number based on the slip velocity.

\[ N_{\text{Re}} = \frac{d_{\text{max}}\rho_c v_{\text{crit}}}{\mu_c} \]  

(3.15)

The equation proposed by Gillespie to compute the drag coefficient is the following:

\[ K_d = F \left[ \frac{24}{N_{\text{Re}}} + \frac{4}{N_{\text{Re}}^{0.468}} + 0.5 \right] \]  

(3.16)

Equation 3.16 gives a conservative estimation of the drag coefficient in quiescent fluid that neglects the sudden drop in value of \( K_d \) associated with reaching the critical Reynolds number. On the other hand, \( F \) is the factor to account for effect of turbulence on \( K_d \). They considered the analysis developed by Lopez and Dukler, which gave a value of \( F = 4 \). This value accounts for some gas turbulence intensity levels. The methodology to calculate the critical gas velocity using the above method is the following:

1. The maximum likely droplet size \( (d_{\text{max}}) \) is calculated using the Equations 3.12 and 3.13.
2. A value of the drag coefficient \( (K_d) \) is assumed. A good initial value may be 0.44.
3. Using the guess value of the drag coefficient, the critical gas velocity is calculated with Equation 3.14.

4. The Reynolds number given by Equation 3.15 is computed with the critical gas velocity obtained in step 3.

5. The drag coefficient given by Equation 3.16 is estimated utilizing the Reynolds's number previously calculated.

6. Again, the critical gas velocity is calculated using the drag coefficient obtained in the previous step.

7. The critical gas velocities from step 3 and 6 are compared; if they are close enough, the process finishes. Otherwise, repeat the procedure from step 3 to 7 until the critical gas velocities are sufficiently close.

Another procedure to calculate the critical gas velocity is given by Kouba et al. They used Taitel, Barnea, and Dukler's mechanistic model. The transition boundary between annular and non-annular flow was developed from a force balance on a droplet of liquid in gas stream. The transition is marked by the minimum gas velocity required to suspend a liquid droplet.

\[ v_{crit} = 1.593 \left[ \frac{\sigma (\rho_d - \rho_c)}{\rho_g^2} \right]^{1/4} \]  \hspace{1cm} (3.17)

The above approach has been used successfully by Coleman to determine when low-pressure gas would begin liquid unloading.

Equation 3.17 was rewritten in terms of standard volumetric flow rate as follows:

\[ q_{gcc} = 4.87 \frac{Ap}{\zeta T} \left[ \frac{\sigma (\rho_d - \rho_c)}{\rho_g^2} \right]^{1/4} \]  \hspace{1cm} (3.18)

When the formation fluid flow rate is lower than the one given by Equation 3.18, the injection liquid will begin to fall below of the injection point.
The critical velocity concept was applied to the condition in a blowout described by Grace. The results are presented in Figure 3.12.

Figure 3.12 displays the estimated critical gas velocity profile utilizing three different approaches. Those velocity profiles were obtained from about 2,300 ft to the beginning of the injection string (nine drill collars). It can be seen that Karabelas' approach gives a critical velocity of 3 ft/s, which means that the kill mud might fall below of the injection point when the in-situ gas velocity has decreased about to 3 ft/s. On the other hand, Kouba's method yields about 9 ft/sec. However the estimated in-situ gas velocity at 2300 ft before starting the control operation is greater than 21 ft/sec and greater than 200 ft/sec when the gas reaches the drill collars. Hence, following the critical velocity theory, this analysis indicates that the gas stream at the injection point would eject the kill
fluid. Consequently, it seems unlikely that the kill fluid would instantaneously stop the gas flow and move downward as envisioned in the momentum kill concept.

3.2.4.2 Analysis of Actual Blowouts Controlled by Applying the Momentum Method

This section describes an analysis of actual blowouts that were controlled by applying the momentum or dynamic kill concept. It was performed with the goal of understanding the actual mechanics of each kill. The three blowouts were originally described in references 8, 9, and 55.

One blowout presented by Grace\(^8\) occurred in Carbon County, Wyoming. It occurred during a washover and backoff operation, with three 6" drill collars above the rotary table and six 7" drill collars below the rotary table. The blowout scenario is presented in Figure 3.13.

Figure 3.13 Blowout conditions given by Grace\(^8\)
In the blowout well, around 30 MMscfd of gas plus water were flowing through the drill collars to the atmosphere. The annular preventer was closed, and the only access to the well was through the kill line. The procedure selected to design the blowout control and calculate the kill parameters was the momentum kill. The momentum force of the gas, \( M_g \) in Equation 3.1, was calculated to be 6.8 lbf, but it was thought that the water increased the total momentum to about 14 lbf. During the control, two kill attempts were performed. First, 12-ppg fluid and a rate of 12 bpm were unsuccessfully employed. These conditions gave a momentum force of the liquid, \( M_{lf} \) in Equation 3.2 of 8.9 lbf. The second kill attempt utilized a 20 ppg kill mud and a rate of 12 to 13 bpm was selected. These kill conditions gave a momentum force of 14.84 lbf. Following the concept of this method, this would be more than the minimum force required to change the gas velocity to zero and then displace if downward through the wellbore if gravitational and drag forces are ignored. The well was successfully controlled, using the selected kill parameters, at a pumping pressure of 1300 psi.

The dynamic kill computer program for this research study was utilized to analyze this kill from the perspective of the dynamic kill concept. The program uses the conventional dynamic method, which considers that only formation fluid is below the injection point. The program computes the pressure gradient in both upper and lower sections considering friction, elevation, and acceleration terms.

Due to the fact that the amount of water flowing in the system was unknown, the calculation considers only gas as blowout fluid. However, this consideration gives lower bottom hole flowing pressures during the dynamic control process than the actual ones, since water increases both the friction and elevation components.

Figure 3.14 shows the wellbore hydraulics performances as solid lines given by the dynamic kill calculation and the kill parameters used to control this well; the dashed curve represents the wellbore hydraulic conditions when only formation fluid is flowing. The reservoir inflow performance was not calculated.
because the reservoir pressure and properties were not reported. However, two reasonable bottomhole pressure conditions were adopted. One bottomhole pressure value was calculated using the gas flow rate of 30,000 Mscf/d reported in the blowout; it is denoted by the triangle. Another bottomhole pressure estimation was obtained considering a normal pressure gradient, which is represented by the circle.

![Wyoming Blowout Bottomhole Flowing Pressure vs Gas Flow Rate](image)

**Figure 3.14 Dynamic kill analysis for the blowout given by Grace**

The curve labeled as "first kill attempt" in Figure 3.14 represents the wellbore hydraulics performance for the conditions given during this attempt. It can be seen that the curve is never completely above the two calculated bottomhole pressure values. That is, the dynamic kill calculations indicate, as shown in the real control operations, that the blowout control cannot be achieved.
employing these kill conditions. On the other hand, the curve labeled as "second kill attempt" stands for the wellbore hydraulic performance obtained utilizing the parameters of the final kill. It is clearly indicated that the curve is always entirely above the two calculated bottomhole pressure values. Consequently, following the dynamic kill concept and as demonstrated by the actual operations, these kill parameters are enough to control the blowout.

Also the three components of the pressure gradient equation (acceleration, friction, and elevation) were calculated at the end of the string at the extreme cases, when only gas is flowing and when the 20 ppg kill fluid is flowing through the drillcollars. The results are presented in Table 3.4

Table 3.4 Magnitudes of steady state pressures for the control given by reference 8

<table>
<thead>
<tr>
<th>Component</th>
<th>Gas flowing</th>
<th>Kill fluid flowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction pressure (psi)</td>
<td>540</td>
<td>1,089</td>
</tr>
<tr>
<td>Elevation pressure (psi)</td>
<td>3.5</td>
<td>281</td>
</tr>
<tr>
<td>Acceleration pressure (psi)</td>
<td>133</td>
<td>0.12</td>
</tr>
<tr>
<td>Pressure at the injection point (psi)</td>
<td>676.5</td>
<td>1,370.12</td>
</tr>
</tbody>
</table>

Table 3.4 shows that the most important factors in this system are the friction and elevation components respectively when the kill fluid is in the wellbore. Consequently, it can be shown that a kill resulting from the momentum forces calculated using the published concept is impossible because the pressure resulting from the change in momentum is insignificant compared to the friction and elevation components.

The pressure profile for the final kill conditions was also estimated for the employed kill parameters. It is presented in Figure 3.15. It shows the pressure just inside of the injection string, nine drill collars, this is, the plot does not consider the pressure gradient from the end of the string to the bottom of the well. It can be seen that the estimated pressure at the bottom of the string is
about 1,400 psi, which may be enough pressure to stop the formation fluid flow and to force some kill fluid to flow downward below the injection depth.

![Pressure Profile](image)

Figure 3.15 Pressure profile through string for the blowout given by Grace\(^8\)

Another blowout described by Grace\(^9\) was also analyzed. It occurred in South Louisiana in the Frio formation. The well was shut in waiting on a pipe line connection. The well head and bottomhole pressure were about 9,700 and 12,000 psi respectively. Three weeks after completion, the tubing acquired a leak resulting in a pressure of 5,400 psi on the 7 5/8" casing. Operations to bleed the casing pressure down were performed and suddenly a sound from below ground level was heard. After that, "surface pressure of all pipe strings" was 4,000 psi, so the presence of an underground blowout was concluded. The well was opened to a pipeline at 30 MMscfd plus 3600 bcpd. It was later determined that the tubing broke at 164 ft, and the casing strings had failed.
Conventional control methods were unsuccessfully applied over a period of six weeks. Therefore, the determination was made to utilize the momentum kill method to design and calculate the kill parameters.

A 1 1/2" injection string was snubbed in to a depth of 1,200 ft through the 2 7/8" tubing. Then, the "momentum" of the blowout fluid was calculated to be 51 lbf. The kill fluid selected was a 19 ppg, 21 cp, ZnBr which was pumped at 8 bpm. Those kill fluid conditions give a "momentum" of 77 lbf. The well was successfully controlled after pumping the selected kill parameters at a pumping pressure of 13,100 psi. The blowout scenario is presented in Figure 3.16.

Figure 3.16 Blowout conditions given by Grace⁹
The computer program built for this research was employed to study this kill. The dynamic kill analysis considered all the elements of the pressure gradient equation in all parts the system. Once again, it was assumed that only formation fluid was present from the end of the kill string to the bottom.

Figure 3.17 Dynamic kill analysis for the blowout given by Grace⁹

Figure 3.17 presents the system analysis approach performed on the blowout of the reference 9. The solid curve depicts the wellbore hydraulic performance for the kill parameters utilized to control the blowout (19 ppg and 8 bpm). The reservoir inflow performance was not calculated because the reservoir properties were not reported. It can be seen that the bottomhole pressure
generated by that density and kill flow rate and considering the conventional dynamic concept is so high that it might be impossible to achieve since the formation fluids would be forced into the producing zone before reaching that bottomhole pressure. Due to this fact, a pressure balance analysis in the system was performed see Figure 18, employing the used flow conditions and observed parameters during the control.

Figure 3.18 Pressure balance analysis performed for the Grace blowout control

Figure 3.18 shows that to meet the flow conditions during the control, 8 bpm were flowing in the injection string with a pump pressure of 13,100 psi. About 2.5 bpm were flowing through the annular section between the 2 7/8"
tubing and 1 1/2" kill string, and approximately 5.5 bpm were being displaced below the injection point. It is important to point out that this analysis does not consider the other boundary condition, the reservoir, due to lack of information. However, it was demonstrated that that the possibility to have kill fluid flow below the injection point exists. And this flow is controlled by the flow conditions, kill flow rate and density, through the annular section.

Another blowout that was analyzed was given by Osornio et al. It occurred in an injection well offshore in Campeche Bay, in the biggest Mexican oil field. The well was being completed in the gas cap zone when a gas kick was taken. It became a blowout due to equipment failure. Formation gas flow rate was estimated to be about 230 MMscfd, and it was flowing through the 9 5/8-injection string that had been run in the hole to 680 m before the well was shut in. The annular preventer was closed, and the only access to the well was through the annular section. The well condition is given in Figure 3.19.

Figure 3.19 Blowout conditions given by Osornio et al.
Two methods were considered for calculating the control parameters: dynamic and momentum kill. Figure 3.20 shows the momentum kill analysis. It can be seen that the required kill rate to reach the force required to change the momentum due to the gas velocity to zero at the injection depth was about 68 bpm of seawater. However, the well was successfully controlled with about 19 bpm, a rate very close to that predicted by dynamic kill technique as documented by the authors\textsuperscript{55}. Therefore, an attempted momentum kill would have required more horsepower, surface pressure and flow rate than necessary to control the well.

![Momentum kill analysis](image)

**Figure 3.20 Momentum kill analysis for the offshore blowout described by Osornio et al\textsuperscript{55}**

A hypothetical oil blowout was also analyzed, since the momentum concept considers a collision between two fluids, and those fluids can be either
gas or liquid. Thus, the theory should also apply for a collision between formation oil and kill fluid.

The information was taken from a real well (tubulars and wellbore geometry, formation and formation fluid properties, etc).

Figure 3.21 presents the conditions during the hypothetical oil blowout. The calculated oil flow rate at those circumstances was about 14,400 bpd flowing up through the wellbore, open hole and casing, and then through the annular section between the 9 5/8" casing and 5" drillpipe.

Figure 3.21 Hypothetical oil blowout conditions utilizing actual data.
After the oil flow rate was estimated, the blowout control was designed and the kill parameters were calculated employing both the momentum kill and dynamic kill concepts.

Figure 3.22 presents the momentum kill analysis with the solid line showing the momentum of the formation fluid through the well. Considering the oil as incompressible fluid with no gas in solution, it can be seen that the "momentum" of the oil from the injection depth to the surface is about 5.9 lbf, and the "momentum" from the injection depth to the bottom is about 3.9 lbf. Therefore, by utilizing seawater as kill fluid, the required kill flow rate to bring the well under control under this concept would be around 9.5 bpm.

\( q_{sf} = 9.5 \text{bpm} \)

Figure 3.22 Momentum kill analysis for the hypothetical oil blowout

A conventional dynamic kill analysis was also performed at the hypothetical oil blowout. Figure 3.23 indicates the results of the system analysis.
approach for the oil blowout. The dashed line represents the reservoir inflow performance, and the solid curves stands for the wellbore hydraulics performance for different kill flow rates of seawater. The bottom curve is the wellbore hydraulics performance when only formation oil is flowing through the well and the kill flow rate is 0 bpm. The intersection of this curve with the IPR curve corresponds to the well condition after all the drilling mud has been unloaded from the wellbore and a free flowing condition has been reached. For this blowout, the calculated oil flow rate was 14,400 bpd. Applying this concept, it can be seen that the required kill rate of seawater to control the well is almost 50 bpm, which is nearly 5 times greater than that given by the momentum method.

**Figure 3.23 Dynamic kill analysis for the hypothetical oil blowout**
The pressure profile was computed for both 10 bpm for "momentum" kill and 50 bpm for dynamic kill, and it was found that the bottom hole pressure generated by the 10 bpm profile was not enough to reach the formation pressure. However, the pressure profile calculated with the 50 bpm kill rate given by the dynamic method yielded a bottom pressure equal to the formation pressure, reducing the implied oil influx rate to zero.

The momentum kill technique indicates that it would be possible to utilize a kill density equal to the oil density, and a kill rate equal to the well flow rate to equalize both momentums and to stop the flow. Thus the kill rate would equal to the formation oil flow rate for any tubular geometry and kill string depth. This result seems inherently illogical unless there are no flow related pressure losses in the formation or in the well below the injection point. Therefore, it is expected that the momentum kill design method in most of the cases will underpredict the kill rate required for an oil or water blowout.

Another conclusion from this oil well analysis is that the dynamic kill method is very sensitive to the injection string depth. If the string length increases, the kill and formation fluid mixture will have more annular section length to generate both friction losses and hydrostatic head, and vice versa if the string length decreases. On the other hand, it can be seen in Figure 3.22 that the momentum concept yields the same kill flow rate, regardless of injection depth, for the same oil flow rate. However, it is known that if the injection depth changes, the total hydraulic system also changes, and consequently the kill flow rate should be different.

3.2.5 Conclusions Regarding the Momentum Method

1. The momentum procedure is supposedly based on Newton’s Second Law of Motion, but it does not consider the external forces (body, tangential, and normal) in its design calculation. That is, the calculation assumes that only the deceleration of the kill fluid mass will stop the formation fluid flow and change
its direction. However, a complete formulation of Newton's Second Law of Motion applied to fluids states that the acceleration of the fluid depends directly on all of the forces in the system.

2. The published momentum kill procedure does not provide a basis for a pressure profile analysis. Therefore, the flow directions and velocities after the collision between the formation and kill fluid and pressures applied to surface and subsurface equipment are unknown. Therefore, confirmation of the effectiveness and safety of the method is not possible with the published method.

3. The analysis of reported momentum kills is possible with a more comprehensive hydraulics model as described herein for dynamic kill. The analysis performed on three actual gas blowouts described by Grace and Osornio et al. confirmed that a successful kill was expected in each case. It also showed that the kill rates used in the momentum kills would easily generate a higher bottomhole pressure than the formation pressure and in effect were higher than the required to kill the well, except in the ambiguous case described in reference 8.

4. A study developed for a hypothetical oil blowout indicated that the kill rate given by momentum concept is not affected by the tubular geometry in the wellbore or by the injection string depth. That is, for a given oil flow rate and kill density, the “momentum force” that will supposedly reduce the oil velocity to zero and displace it downward through the wellbore will be always the same. It is expected that the momentum kill design method will underpredict the kill rate necessary for an oil blowout.
CHAPTER 4

DYNAMIC SEAL – BULLHEADING METHOD

The previous chapter presented an analysis of the current off-bottom blowout control methods, and identified some operational and design shortcomings. In addition, the risk of having more complex blowouts increases due to deeper, higher pressure and higher technology wells. Therefore, it is important to investigate different alternatives to regain control in a rapid and effective way and to minimize blowout consequences.

The primary goal of this research was to develop an engineering procedure to assist designing and predicting all kill parameters for a successful and efficient off-bottom kill job by pumping control fluid through an injection string in the well. The model developed in this dissertation called "dynamic seal-bullheading" allows the kill parameters such as kill flow rate, kill density, required kill fluid volume, pumping time, and effect of control depth to be known. The model also allows the formation fluid influx rate, surface pressure, bottomhole pressure, and pressure at critical points in the well to be calculated as function of time. The mathematical procedure was implemented in an Excel spreadsheet using macros. This chapter describes the analytical models used, the global solution scheme, and some example applications of the method.

4.1 Principle

The conceptual basis of the dynamic seal-bullheading method involves two important stages in the control process. First, a dynamic seal has to be generated at the injection string depth, which will force a portion of the kill fluid to flow downward from the string depth in a controlled way. Second, this kill fluid flowing downward will force the remaining formation fluid in the wellbore back into the permeable zone or other open formation, which is essentially a bullheading process.
A dynamic seal is a hydraulic seal that is developed when the pressure required to push fluids through a flow path to the surface exceeds the pressure required for a hydrostatic balance with the formation pressure. It is generated by pumping kill fluid down through the injection string to establish a mixture of formation and kill fluids flowing from the injection depth to the surface increasing the pressure due to hydrostatic head, frictional pressure drop and acceleration at the injection depth. The pressure depends directly on both kill flow rate and kill density. Hence the dynamic seal is attained when the pressure at the injection point depth generated by the pumping conditions is high enough to force the kill fluid downward.

The dynamic seal generation is schematically illustrated in Figure 4.1, which presents an off-bottom blowout scenario. Figure 4.1a indicates the initial well conditions when only formation fluid is flowing in the system. The solid line denotes the flowing gas pressure profile from the bottom to the surface. The flow path is through the openhole, casing and annulus. The dashed line represents the static gas pressure in the injection string.

On the other hand, Figure 4.1b presents the well conditions a few minutes after the control is started. The solid line, labeled \( q_{k_f(1)} \), is the pressure profile given by the rate, \( q_{k_f(1)} \), of a selected fluid density once the pumping operation has reached steady state conditions. The solid line, labeled \( q_{k_f(2)} \), represents the pressure profile yielded by a higher rate of, \( q_{k_f(2)} \), and so on for the line labeled as \( q_{k_f(3)} \). In this illustration, the greatest rate is \( q_{k_f(3)} \), the lowest one is \( q_{k_f(1)} \), and an intermediate rate is given by \( q_{k_f(2)} \). It can be seen that the bottomhole pressure increases with the kill rate until the injection pressure is reached. When the formation fluid just begins to flow into a permeable zone, the dynamic seal has been attained at the kill string depth. Then those parameters, rate and density, are the ones needed to achieve the hydraulic seal.
Figure 4.1a Initial conditions of the dynamic seal generation

Figure 4.1b Dynamic seal process
Following the concept of dynamic seal - bullheading, once the hydraulic seal has been reached at the injection string depth, the formation fluid can be displaced into the permeable formation by the kill fluid. This operation is practically a bullheading process. The bullheading process is a kill method in which the kill fluid forces the formation fluid back into the formation. The second stage of this procedure is schematically illustrated in Figure 4.2.

Figure 4.2a Bullheading process
The bullhead process is shown in Figure 4.2a. The solid line is the pressure profile in the system during the final phase of the control, and the dashed line displays the pressure inside of the kill string. It can be seen that during this stage there will be kill fluid flowing in two directions from the injection depth to the surface, to maintain the hydraulic seal, and from the injection depth to the bottom, a bullhead operation. Therefore, it is important to take into account these two rates to obtain the surface kill flow rate. If they are not considered then once the control fluid begins to flow down, the pressure profile will change in the system due to mass fraction of the kill fluid going below the injection point instead of going into the annulus, and the dynamic seal could potentially be lost. As a consequence the control of the well may be lost.

![Diagram of bullhead process](image)

**Figure 4.2b** Final phase of the blowout control utilizing the proposed method
Figure 4.2b displays the final phase of the control. The solid line represents the pressure profile in the well in static conditions. This procedure utilizes only one kill density during the control operation. The chosen fluid density would be the one that generates a hydrostatic pressure at the bottom between the formation pressure and the injection pressure, see Figure 4.2b.

It was previously shown that the proposed method considers two important stages, which were individually considered. Therefore, two models had to be created: one to obtain the dynamic seal and another to describe the bullheading operation. In this work the two models were analyzed, built, and programmed separately; then they were coupled to obtain the final one.

4.1.1 Dynamic Seal Mathematical Model

The dynamic seal mathematical model involves two major components, the wellbore and the reservoir. These were coupled, since a variation of the flow conditions in the wellbore will inevitably cause a modification to the reservoir performance. The link between these two sections was the face of the production zone.

The dynamic seal analysis considered four sections in the system, three in the wellbore and one in the reservoir. Figure 4.3 illustrates a typical off-bottom blowout with the four zones to model the different areas of interest in the system. Zone 1 represents the producing formation, which produces the uncontrolled flow of formation fluid toward the surface. Zone 2 is in the wellbore and represents the section of single-phase, formation fluid, flow from the bottom of the well to the injection string depth. Zone 3 is also in the wellbore and represents the two-phase flow generated by the formation fluid and the kill fluid flowing through the annular section, from the string depth up to the surface once the pumping operations begin. Finally zone 4 contains the single-phase control fluid flow down through the kill string.
The mathematical model for each zone is explained in the following sections.

**4.1.1.1 Model Assumptions**

The following assumptions and considerations have been made in developing the dynamic seal model.

- The flow system has one-dimensional spatial geometry along wellbore due to the limited cross sectional size compared with the axial wellbore length
- The temperature gradient is constant and known
- The formation fluid is single phase gas or liquid
- The kill fluid has constant properties
- Only single phase flow exists below the injection point until a dynamic seal is achieved
- The injection rate of the kill fluid is constant
- No mud moves down into zone 2 until bottomhole pressure exceeds formation pressure
Flow rate of mud moving up annulus is constant after injection pressure is achieved.

Kill is complete when mud is bullhead to the formation face

The producing formation is isotropic and the flow is radial

4.1.1.2 Wellbore Model

The wellbore model considers three zones, which were previously defined, see Figure 4.3. The equations employed to model the flow process in those zones are the conservation of linear momentum, conservation of mass, equation of state, gas velocity equation, and fluid and PVT property correlations. The conservation of linear momentum \( \frac{\partial}{\partial t} (\rho v^2) + \frac{\partial}{\partial L} (\rho v) = -\frac{\partial}{\partial L} \frac{fpv^2}{2d} + \rho g \) is given by

\[
\frac{\partial}{\partial t} (\rho v^2) + \frac{\partial}{\partial L} (\rho v) = -\frac{\partial}{\partial L} \frac{fpv^2}{2d} + \rho g
\]  

(4.1)

The Conservation of Mass \( \frac{\partial}{\partial t} (\rho) + \frac{\partial}{\partial L} (\rho v) = 0 \) is represented by

\[
\frac{\partial}{\partial t} (\rho) + \frac{\partial}{\partial L} (\rho v) = 0
\]  

(4.2)

The combination of the above equations gives the well-known pressure gradient equation, given by

\[
\left( \frac{dp}{dL} \right)_t = \left( \frac{dp}{dL} \right)_f + \left( \frac{dp}{dL} \right)_{el} + \left( \frac{dp}{dL} \right)_{acc}
\]  

(4.3)

The derivation of the pressure gradient equation is presented in Appendix B. The left-hand side term of Equation 4.3 is the total pressure gradient of the fluid in the interval studied. The first right-hand-side term accounts for frictional pressure losses due to the viscous shearing stress between the fluid and the
wellbore/pipe wall and always causes a drop of pressure in direction of the flow. It is given in field units by

\[
\left( \frac{dp}{dL} \right)_f = \frac{fpv^2}{772.17d}
\]  

(4.4)

The second right-hand-side term accounts for the hydrostatic pressure of the fluid and acts in the direction of the gravitational field. It is given by

\[
\left( \frac{dp}{dL} \right)_{el} = \frac{\rho}{144}
\]  

(4.5)

The third right-hand-side component accounts for pressure changes caused by fluid acceleration; a pressure drop occurs in the direction that the velocity increases. It is represented by

\[
\left( \frac{dp}{dL} \right)_{acc} = \frac{\rho \Delta v^2}{9273.6\Delta L}
\]  

(4.6)

The friction pressure loss component represented by Equation 4.4 involves the calculation of the friction factor \( (f) \) which strongly depends on the rheological model of the fluid, i.e., whether the control fluid follows Newtonian or non-Newtonian behavior.

4.1.1.2.1 Newtonian Kill Fluids

Newtonian fluids such as water and brines are sometimes used in well control operations. The primary peculiarity of the Newtonian fluids is that the shear stress \( (\tau) \) is directly proportional to the shear rate \( (\dot{\gamma}) \). The mathematical model is given by

\[
\tau = \mu \dot{\gamma}
\]  

(4.7)
where $\mu$ is the constant of proportionality and is known as the viscosity of the fluid.

The friction factor in the friction term of the pressure gradient equation has not been analytically characterized except for laminar, single-phase flow. Hence it must be calculated by experimental work for turbulent flow. The friction factor is a function of both Reynolds number ($N_{Re}$) and relative roughness ($\varepsilon$). The Moody friction factor ($f'$, dimensionless), which is four times larger than the fanning friction factor ($f''$), is adopted through this work.

$$f' = 4f'' \quad (4.8)$$

The procedure to evaluate the friction factor requires knowing whether the flow is laminar or turbulent. Laminar flow (considered to exist if the Reynolds number is less than 2,100) is calculated as follows:

$$f = \frac{64}{N_{Re}} \quad (4.9)$$

Turbulent flow has no analytical representation, but several empirical equations have been proposed. In this work, the friction factor for non-Newtonian turbulent flow is calculated using the Serghides' equation\textsuperscript{45}. It is an explicit approximation to the Colebrook's correlation\textsuperscript{34}. Serghides' formula avoids the iterative solution and gives a maximum deviation of 0.0023%. It is given by

$$f = \left( A_7 - \frac{(A_8 - A_7)^2}{A_9 - 2A_8 + A_7} \right)^{-2} \quad (4.10)$$

where:

$$A_7 = -2\log\left( \frac{\varepsilon/d}{3.7} + \frac{12}{N_{Re}} \right)$$
When the flow is through the annular section, \( d \) is computed using the equivalent circular diameter concept\(^1\) which is given by

\[
d_e = 0.816(d_2 - d_1)
\]  
(4.11)

where:
- \( d_e \) = Equivalent diameter (in).
- \( d_1 \) = External diameter of injection pipe (in).
- \( d_2 \) = Internal diameter of outer pipe or borehole (in).

![Diagram of flow through annular section](image)

Figure 4.4 Flow through annular section

The Reynolds number, \( N_{Re} \) (dimensionless), is defined by

\[
N_{Re} = \frac{124 \rho v d}{\mu}
\]  
(4.12)

The same equation can be used for flow through pipe or annulus, using \( d \) or \( d_e \), respectively.
4.1.1.2.2 Non - Newtonian Kill Fluids

During well control operations, it is sometimes necessary to use a higher fluid density than water to control the well. Naturally this will depend on the productive zone properties. The only two ways to obtain those densities are by using either brines or drilling muds, but due to the cost and simplicity to prepare them in high densities, the most common kill fluids are muds. A complication is that those fluids have non-Newtonian behavior. That is, they do not exhibit a direct proportionality between shear stress and shear rate, making them more difficult to characterize. The non-Newtonian fluids used in drilling operations are pseudoplastic, fluids whose apparent viscosity decreases with increasing shear rate. The Bingham plastic and power law rheological models are most commonly utilized to represent a pseudoplastic behavior. In this work, the power law model will be adopted to represent the non-Newtonian behavior of the kill fluid.

The power law fluids, like Newtonian fluids, will flow under any applied stress. However, as distinct from Newtonian fluids, the shear stress is not proportional to the shear rate, but to its \( n \)\(^{th} \) power. It is defined by

\[
\tau = K\dot{\gamma}^n \tag{4.13}
\]

This model requires two parameters for fluid characterization\(^1\). One of them is \( K \), consistency index, and is indicative of the pumpability or overall thickness. The other parameter is \( n \), flow behavior index, and it can be considered as a measure of the degree of deviation of a fluid from Newtonian behavior. For \( n = 1 \), the Equation 4.13 becomes the Newtonian fluid equation. The units of the consistency index (\( K \)) depend on the value of \( n \). \( K \) has units of dyne-s\(^n\)/cm\(^2\). In this work, a unit called equivalent centipoise, eq cp, will be used to represent 0.01 dyne-s\(^n\)/cm\(^2\).

The determination of the flow behavior index (\( n \)) is computed with the following equations\(^1\):
\[ n = 3.322 \log \left( \frac{\theta_{600}}{\theta_{300}} \right) \]

or

\[ n = \frac{\log \left( \frac{N_2}{N_1} \right)}{\log \left( \frac{N_2}{N_1} \right)} \]  
\[ \text{(4.14)} \]

On the other hand, the consistency index is calculated as follows

\[ K = \frac{510 \theta_{300}}{511^n} \]

or

\[ K = \frac{510 \theta_N}{(1.703N)^n} \]  
\[ \text{(4.15)} \]

The dial readings used in these equations are measured with a standard Fann viscometer.

For fully developed laminar flow, the friction losses can be predicted by the Metzner - Reed equations\(^1\). For pipe it is given by

\[ \frac{dp}{dL} = \frac{K \bar{v}^n}{144,000d^{1+n}} \left( \frac{3 + \frac{1}{n}}{0.0416} \right) \]  
\[ \text{(4.16)} \]

For the annulus the pressure loss gradient is given by
\[
\frac{dp}{dL} = \frac{Kn}{144,000(d_2 - d_1)^{1+n}} \left( \frac{2 + \frac{1}{n}}{0.0208} \right)^n
\] (4.17)

Where \(\frac{dp}{dL}\) is the frictional pressure gradient when laminar flow is present.

The friction factor for turbulent non-Newtonian flow is calculated utilizing the Dodge and Metzner method\(^{34}\). They suggested an implicit friction factor equation, which is calculated in an iterative procedure and is given by

\[
\sqrt{f'} = \frac{4}{n^{0.75}} \log \left( N_{Re, f'} \left( \frac{1}{n} \right)^{\left( \frac{1-n}{2} \right)} \right) - \frac{0.395}{n^{1.2}}
\] (4.18)

The Reynolds number\(^{67}\) is calculated utilizing the apparent Newtonian viscosity

\[
N_{Re, \mu_a} = \frac{124 \rho \bar{v} d}{\mu_a}
\] (4.19)

Again the internal pipe or borehole diameter is used for pipe flow, and the equivalent diameter concept using Equation 4.11 is utilized for flow through annulus. The apparent viscosity\(^{67}(\mu_a)\) for flow through pipe is given by

\[
\mu_a = \frac{Kd \left( \frac{1-n}{2} \right)}{96 \bar{v} \left( \frac{1-n}{2} \right)} \left( \frac{3 + \frac{1}{n}}{0.0416} \right)
\] (4.20)

On the other hand, the apparent viscosity for flow through annular section is computed by
\[ \mu_a = \frac{K(d_2 - d_1)^{(l-n)}}{144\pi^{(l-n)}} \left( \frac{2 + \frac{1}{n}}{0.0208} \right) \] (4.21)

The computer program will calculate the frictional pressure losses for both laminar and turbulent flow. Then, the larger value will be chosen as the correct one. This will avoid dependence on Reynolds number criteria.

Other parameters and fluid properties such as density, viscosity, and velocity are required to compute the friction factor and the total pressure gradient.

In-situ gas density is a function of pressure and temperature and will be calculated utilizing the real gas law\(^20\), which is given by

\[ \rho_g = 2.7 \gamma_g \frac{p}{zT} \] (4.22)

Here \( \gamma_g \), is the specific gravity of the gas and is given by the ratio of the molecular weight of the gas \( \hat{M}_g \) to the molecular weight of dry air. It can be calculated by

\[ \gamma_g = \frac{\hat{M}_g}{28.96} \] (4.23)

The gas compressibility factor \( z \) is computed using the Dranchuk & About - Kassem equation\(^20\), which is a fitted equation of state to the data of Standing and Katz\(^23\). It is given by the following equations.
\[ z = 1 + \left( \frac{A_1 + A_2}{T_{pr}} + \frac{A_4}{T_{pr}^3} + \frac{A_5}{T_{p}^4} + \frac{A_8}{T_{pr}^5} \right) \rho_r + \left( \frac{A_6 + A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2} \right) \rho_r^2 \]
\[ - A_9 \left( \frac{A_7}{T_{pr}} + A_8 \right) \rho_r^3 + A_{10} \left( 1 + A_{11} \rho_r^2 \right) \left( \frac{\rho_r^2}{T_{pr}^3} \right) \exp \left( - A_{11} \rho_r^2 \right) \]  

(4.24)

\[ \rho_r = 0.27 \left[ \frac{p_{pr}}{zT_{pr}} \right] \]

\[ p_{pr} = \frac{p}{p_{pc}} \]

\[ T_{pr} = \frac{T}{T_{pc}} \]

\[ p_{pc} = 756.8 - 131 \gamma_g - 3.6 \gamma_g^2 \]
\[ T_{pc} = 169.2 + 349.5 \gamma_g - 74 \gamma_g^2 \]

where the constants \( A_1 - A_{11} \) are as follows:

\[
\begin{align*}
A_1 &= 0.3265 & A_3 &= -0.05165 & A_4 &= 0.1056 \\
A_2 &= -1.0700 & A_5 &= 0.5475 & A_{10} &= 0.6124 \\
A_3 &= -0.5339 & A_7 &= -0.7361 & A_{11} &= 0.7210 \\
A_4 &= 0.01569 & A_8 &= 0.1874 
\end{align*}
\]

The viscosity is utilized for determining the Reynolds number. In this work the in-situ gas viscosity (\( \mu \)) is calculated using the Carr, Kobayashi, and Burrows correlation\(^{23} \). This correlation takes into account both fluid pressure and temperature for each calculation. It is given by

\[ \mu = \left( 1.709 \times 10^{-5} - 2.062 \times 10^{-6} \gamma_g \right) T + 8.188 \times 10^{-3} - 6.15 \times 10^{-3} \log \gamma_g \]
The ratio of $\mu / \mu_1$ is evaluated from

$$\ln \left( \frac{\mu}{\mu_1} T_{pr} \right) = a_0 + a_1 p_{pr} + a_2 p_{pr}^2 + a_3 p_{pr}^3 + T_{pr} \left( a_4 + a_5 p_{pr} + a_6 p_{pr}^2 + a_7 p_{pr}^3 \right)$$

$$+ T_{pr}^2 \left( a_8 + a_9 p_{pr} + a_{10} p_{pr}^2 + a_{11} p_{pr}^3 \right) + T_{pr}^3 \left( a_{12} + a_{13} p_{pr} + a_{14} p_{pr}^2 + a_{15} p_{pr}^3 \right)$$

where the constants $a_0 - a_{15}$ are given by

$a_0 = -2.46211820 \times 10^0$
$a_1 = 2.97054714 \times 10^0$
$a_2 = -2.86264054 \times 10^{-1}$
$a_3 = 8.05420522 \times 10^{-3}$
$a_4 = 2.80860949 \times 10^0$
$a_5 = -3.49803305 \times 10^0$
$a_6 = 2.60373020 \times 10^{-1}$
$a_7 = -1.04432413 \times 10^{-2}$
$a_8 = -7.93385684 \times 10^{-4}$
$a_9 = 1.39643306 \times 10^0$
$a_{10} = -1.49144925 \times 10^{-1}$
$a_{11} = 4.41015512 \times 10^{-3}$
$a_{12} = 8.39387178 \times 10^{-2}$
$a_{13} = -1.86408848 \times 10^{-1}$
$a_{14} = 2.03367881 \times 10^{-2}$
$a_{15} = -6.09579263 \times 10^{-4}$

Finally the gas viscosity is obtained by:

$$\mu_g = \frac{\mu_1}{T_{pr}} \exp \left[ \ln \left( \frac{\mu}{\mu_1} T_{pr} \right) \right]$$

The in-situ gas velocity ($v_g$) is defined as

$$v_g = \frac{q_g}{A}$$

but:

$$q_g = q_{gscd} B_g$$

where $B_g$ is the gas formation volume factor and is calculated from the gas real law as follows:
Combining the above expressions and writing the gas velocity in practical units:

\[ v_g = 3.2743 \times 10^{-7} \frac{q_{gcd} zT}{pA} \]  

(4.28)

Where \( A \) is the flow area, it can be pipe or annular.

Once the kill fluid reaches the injection point, there will be a mixture of the kill fluid and the formation fluid from the string depth to the surface. Therefore a two-phase flow model should be used for determining pressure losses.

Kouba\textsuperscript{33} presented an analytical method that considers homogeneous flow for calculating the pumping requirements to achieve a dynamic kill. He concluded that the homogeneous model is very accurate at high flow rates. Fan Jun et al\textsuperscript{44} developed a transient on-bottom dynamic model for killing of a single-phase gas blowout. They also adopted a homogeneous model, since they considered that the gas flow system is of rather high flow rate at the principal stages in kill process. This has been proven accurate enough to characterize flow in the mist flow regime. Oudeman et al.\textsuperscript{54} designed, executed, and analyzed a full-scale field test to study how a dynamic kill proceeds in gas wells. They obtained excellent results with the homogeneous flow model, reportedly because at the high flow rates encountered in the blowing well, slip between gas and liquid do not play an essential role, and the refined multiphase flow models did not yield answers essentially different from the homogeneous model.

In this dissertation, a conventional dynamic kill model was also built considering homogeneous flow. It was then run with data from the blowout that occurred in Mobil Indonesia’s Arun field\textsuperscript{32}. The results showed excellent agreement with results from other models\textsuperscript{32, 33, 53} that used the same information.
to calculate the kill parameters, see Table 3.2, even though the model given by Al-Sheri\textsuperscript{53} is a rigorous two-phase flow model.

The homogeneous flow pattern was adopted for modeling the dynamic seal generation phase because it gives reliable results in high flow rates, which are present during this process. Therefore, the pressure gradient equation (Equation 4.3) for a two-phase flow mixture becomes

\[
\left( \frac{dp}{dL} \right) = \frac{f \rho_m v_m^2}{772.17d} + \frac{\rho_m}{144} + \frac{\rho_m \Delta v_m^2}{9273.6\Delta L}
\]  \hspace{1cm} (4.29)

where \( \rho_m \) is the mixture density\textsuperscript{22}, which can be calculated as

\[
\rho_m = \rho_{sf} \lambda + \rho_g \alpha
\]  \hspace{1cm} (4.30)

The volumetric fraction of the control liquid (\( \lambda \))\textsuperscript{34} also called liquid holdup, is defined as the ratio of the volume occupied by the liquid component of the total volume and is given by

\[
\lambda = \frac{8085.6q_{sf}}{8085.6q_{sf} + q_g}
\]  \hspace{1cm} (4.31)

Here \( q_g \) is in-situ conditions and is defined by Equation 4.26. The formation fluid would occupy the remainder of the pipe segment, and for gas wells it is referred to as gas void fraction or gas holdup. It is obtained by

\[
\alpha = 1 - \lambda
\]  \hspace{1cm} (4.32)

The term, \( v_m \), in Equation 4.29 is the mixture velocity\textsuperscript{34}, which is defined as the sum of superficial velocities of both fluid components. It can be estimated by
The in-situ gas velocity \( v_m \) is given by Equation 4.28 and the kill fluid velocity \( v_{kf} \) can be calculated by

\[
v_{kf} = \frac{17.16 q_{kf}}{d^2}
\]  

(4.34)

The Reynolds number of the mixture \(^3\) is given by

\[
N_{Re} = \frac{124 \rho_m v_m d}{\mu_m}
\]  

(4.35)

where \( \mu_m \) is the mixture viscosity \(^2\) which can be computed by

\[
\mu_m = \mu_{kf} \mathcal{A} + \mu_g \mathcal{C}
\]  

(4.36)

Again, the internal pipe or borehole diameter is used for pipe flow, and the equivalent diameter concept in Equation 4.11 is utilized for flow through annulus.

The in-situ gas viscosity is given by Equation 4.25.

### 4.1.1.3 Reservoir Model

Another major section that is involved in the dynamic seal model is the reservoir, shown as zone 1 in Figure 4.3. As the conditions change in the wellbore, the producing zone will inevitably respond. In well control operations, the desired response is a decrease in the formation fluid influx rate. Therefore, a reservoir model should be coupled to the wellbore.
The reservoir model is based on the well-known Darcy's law\textsuperscript{69}, which is a mathematical relationship between formation flow rate and pressure drop in the reservoir. It states that the velocity of a fluid in a porous medium is proportional to the driving pressure and inversely proportional to the fluid viscosity.

For gas blowouts where the flow in the vicinity of the wellbore occurs at higher velocities, an additional pressure drop in the system takes place due to convective acceleration of the fluid passing through the pore space. Therefore, a non-Darcy term is taken into account. Under these circumstances, the appropriate flow model is the Forchheimer's equation\textsuperscript{56}, which is given by

\[
p_R^2 - p_{bh}^2 = Xq_{gcd} + Yq_{gcd}^2
\]

(4.37)

In the above equation (X) is the Darcy component or pressure drop due to laminar flow, and it is given by

\[
X = \frac{1.422 \mu_e z_R T_R}{kh} \left[ \ln \left( \frac{0.472 r_e}{r_w} \right) \right]
\]

(4.38)

On the other hand, the term (Y) is the non-Darcy flow component or pressure drop due to turbulence of the gas around the wellbore. It is mathematically represented by

\[
Y = \frac{3.16 \times 10^{-18}}{k^2} \beta \gamma_e z_R T_R \left( \frac{1}{r_w} - \frac{1}{r_e} \right)
\]

(4.39)

Where \( \beta \) is the coefficient of inertial resistance, also called the turbulence factor, and is determined from an experimental relationship\textsuperscript{26}. The turbulence factor depends on formation permeability and it is given by
\[ \beta = \frac{10^7}{\sqrt{k}} \quad \text{for} \quad k \geq 5,000 \text{md} \quad (4.40) \]

and

\[ \beta = \frac{3.55 \times 10^{10}}{k^{1.35}} \quad \text{for} \quad k \leq 5,000 \text{md} \quad (4.41) \]

The gas formation properties in Equation 4.38 and 4.39 are calculated at reservoir conditions.

Solving the quadratic equation, Equation 4.37, it is possible to compute the deliverability potential of the reservoir as a function of differential pressure between the face formation and the producing formation limits.

\[ q_{gscd} = \frac{-X + \sqrt{X^2 + 4Y(p_R^2 - p_{bh}^2)}}{2Y} \quad (4.42) \]

It can be seen in Equation 4.42 that the gas flow rate is a function of the difference between reservoir pressure and bottomhole pressure, formation properties, formation fluid properties, and flow turbulence.

**4.1.1.4 Formation Fluid Rate Determination**

The formation fluid flow rate is estimated initially when the well has been completely unloaded of all the drilling mud and free flowing equilibrium conditions have been reached. That is, only formation fluid is flowing in the system from the reservoir to atmosphere. Under this situation, the mathematical relationship between the wellbore and the producing zone yields the maximum formation flow rate that is possible given the well geometry. These conditions are considered as the initial conditions of the well control procedure.
The formation fluid flow rate depends on two important components, the reservoir inflow performance (IPR) and the wellbore hydraulics performance (WHP), also called inflow and outflow performance, respectively.

The IPR is the relationship between the production rate from the reservoir and bottomhole pressure and is a measure of the formation's capacity to produce to the wellbore. In this work, the IPR will be estimated by solving Equation 4.37 for the bottomhole pressure, in the form shown as Equation 4.43

$$p_{bh}^2 = p_R^2 - \left( \frac{1.422 \mu_g z_R T_R}{kh} \ln \left( \frac{0.472 r_e}{r_w} \right) \right) \frac{q_{gcd}}{g_{sced}} - \left\{ \frac{3.16 \times 10^{-18} \beta \gamma_g z_R T_R \left( \frac{1}{r_w} - \frac{1}{r_e} \right)}{h^2} \right\} \frac{q_{gcd}}{g_{sced}}$$

(4.43)

The formation fluid properties such as the gas deviation factor ($z_R$) and gas viscosity ($\mu_g$) are calculated with Equations 4.24 and 4.25, respectively. Then several gas flow rates are assumed and the bottomhole pressure is calculated for each specific rate employing Equation 4.43. The resulting reservoir inflow performance curve is plotted on a graph of gas flow rate versus bottomhole pressure.

On the other side, the WHP is the relationship between the production rate and the bottomhole pressure generated by that rate flowing to the surface through the wellbore. In this work, the WHP at the initial conditions with only gas flowing in the system will be calculated utilizing the Cullender and Smith equation\(^{21}\), which is given by

$$\frac{1,000 \gamma_g L}{53.356} = \int_{p_{min}}^{p_r} \frac{p}{T_z} \frac{0.667 f q_{gcd}}{d^3} + \frac{1}{1,000} H \left( \frac{p}{T_z} \right)^2$$

(4.44)
This is the most widely used method to calculate flowing bottomhole pressure in gas wells\textsuperscript{34}. The Cullender and Smith method makes no simplifying assumptions for the variation of temperature and gas deviation factor in the wellbore. Consequently, the procedure is more accurate than other proposed methods. Equation 4.44 can be solved applying the trapezoidal rule for numerical integration\textsuperscript{34,64}.

When gas flow is through an annular section, the following equation for the diameter is used in Eq. 4.44:

\[ d^5 = 0.816(d_2 - d_1)(d_2^2 - d_1^2)^2 \]  \hspace{1cm} (4.45)

where \( d_2 \) and \( d_1 \) are schematically shown in Figure 4.4.

The friction factor (\( f \)) and gas deviation factor (\( z \)) are calculated with Equations 4.10 and 4.24 respectively. Again several gas flow rates are assumed, and the bottomhole pressure is calculated for each specific rate, employing Equation 4.44. The resulted wellbore hydraulics performance curve is superimposed on the same graph as the IPR curve.

The simultaneous solution of the reservoir inflow performance and wellbore hydraulics performance is given at the intersection point between the curves generated by those Equations 4.43 and 4.44, representing the natural flow point for that system. Thus, the conditions at that intersection point yield both the formation fluid flow rate and the flowing bottomhole pressure when only formation fluid is flowing through the wellbore.

Figure 4.5 displays a typical relationship between the IPR and the WHP. It can be seen that the intersection point is the natural flow point of the well and gives both the bottomhole pressure and the formation fluid flow rate when only formation fluid is flowing.
Once the gas flow rate is known, it is employed in Equation 4.44, and the pressure profile in the system from the bottom to the surface is estimated. Chapter 5 will present a real calculation of these parameters.

**Figure 4.5** Formation fluid rate and bottomhole flowing pressure determination

### 4.1.1.5 Global Solution Scheme

The wellbore model and the reservoir model were coupled at the sand face to obtain a global solution as a basis for computing the flow conditions in the wellbore during the control process as a function of axial position at selected times. The solution scheme for applying the dynamic seal mathematical model utilizes a series of fully steady states solutions assuming that a given steady state flow condition exists for the time for the mixture creating those conditions to reach the surface. By employing this approach, the approximate effect of time
can be included in the process. As a consequence, the kill fluid volume required to reach the dynamic seal can be obtained.

The solutions using this scheme predict the pressure behavior at any point in the wellbore and in the injection string as a function of spatial location along the flow path at selected times. The solution requires the specification of initial and boundary conditions to solve the flow equations.

4.1.1.5.1 Initial Conditions

The initial conditions are determined when the formation fluid has completely unloaded the well of all the drilling fluid. Under this circumstance, only formation fluid is flowing in the system, and the equilibrium conditions have been reached. At this point, the formation flow rate and pressure profile from the surface to the bottom are calculated in the system as described in the previous section. Thus it is assumed that the blowout well has been flowing at a constant rate for a period of time such that steady state flow has been achieved inside the wellbore before and at the instant that the killing operation starts.

The wellbore is discretized into cells or grids of equal length along the length of the well. Hence, knowing the formation fluid flow rate, flowing bottom hole pressure, surface pressure, geothermal temperature gradient, and cell length, the initial conditions along the wellbore can be estimated.

The initial distribution of density, viscosity, flow rate, velocity, and pressure gradient along the axial position can be computed utilizing Equations 4.22, 4.25, 4.26, 4.28 and 4.3, respectively, and a pressure traverse procedure as discussed in the next section. The process of calculating the initial distribution of conditions is schematically presented in Figure 4.6.

The pressure traverse procedure is applied at each cell and marching downward until reaching the bottom of the well. The velocity is corrected for changes in cross sectional area.
4.1.1.5.2 Boundary Conditions

With a surface blowout in process, it is assumed that the pressure and temperature conditions at the surface are known. So one known boundary condition is at the surface during the entire dynamic seal process. Another boundary is at the bottom of the well, where the wellbore is connected with the producing formation with known fluid properties and rock properties. Therefore, after the kill begins and a new bottomhole pressure is obtained by applying the pressure traverse procedure started at the surface, the reservoir mathematical model can be used to give a new formation fluid rate. This will be utilized to
obtain the new distribution of densities, viscosities, velocities, flow rates, fluid fractions, and pressure gradient for a given time step.

The global solution procedure to describe the dynamic seal process is as follows. After the formation fluid rate and the pressure profile in the system have been computed, the initial fluid flow conditions throughout the wellbore are calculated, as described in the initial conditions section, utilizing the surface boundary condition. Then, the control operations begin by pumping a control fluid of a given density and with constant properties at a given rate downward through the injection string or down the annulus if the blowout is up the inner string.

The calculation procedure starts when the kill fluid is at the injection depth, that is just after the first droplet of liquid leaves the injection string and flow to the annulus. However, the time to fill the injection string is considered in the process. Therefore, the predictions of pressures while establishing a dynamic seal begin at the time required to fill the drillstring. Time zero or time at zero seconds is when the pumping operations just begin and the kill fluid is pumped into the injection string at the surface.

The dynamic seal model performs the calculation of the time based on the mixture velocity. That is, if we know the cell length and the mixture velocity the program calculates the time required to travel from one cell to other. This procedure is performed at each cell until the kill fluid fills completely the annular section. The program then sums these times to obtain an estimate of the time required for fluids to reach the surface after a change in fluid input rates at the injection point.

For the case of a blowout up the annulus, the calculation procedure starts at the surface of the annular section considering the initial formation fluid rate and the kill fluid rate, expressed at standard conditions, as constant and equal in each cell. Then the pressure traverse for each cell is applied downward, using the wellbore mathematical model given in the earlier section, until it reaches the bottomhole. The fluid flow conditions along the wellbore and the bottomhole pressure can be determined for a specific time step. With the new bottomhole
pressure, a new formation fluid rate is calculated utilizing the reservoir model as the boundary condition equation. Employing the new formation fluid rate, and the kill rate, the whole procedure is repeated to obtain the flow conditions, pressure gradient, and a formation fluid rate for a new time step. This process is schematically presented in Figure 4.7.

Another flow condition is given for the injection string since single-phase kill fluid is flowing downward through it after the control starts. The pressure condition in the tubing and at the surface is obtained utilizing the pressure at the injection depth as a starting point. Then the upward pressure traverse calculation for single-phase flow is applied until reaching the surface. This procedure is also repeated for each time step.

Figure 4.7 Wellbore conditions after the first time step is taken
4.1.1.5.3 Pressure Traverse Calculation

The pressure traverse calculation for a two-phase flow is a procedure that calculates the pressure gradient along the wellbore\textsuperscript{22}. It employs the pressure gradient equation for a two-phase flow mixture (Equation 4.29) as well as the multi-phase flow properties given from Eq 4.30 to Eq 4.36.

The procedure is started at the top after applying the boundary conditions and marches downward over small length increments, considering the pipe geometry changes, until the bottom of the well is reached. The mixture properties are evaluated at average pressure and temperature in small increments. Then the pressure gradient is iteratively computed for each cell until a tolerance value of 0.00001 psi on the upstream pressure is attained. The following procedure explains the pressure traverse calculation to obtain the pressure gradient along the wellbore. The procedure is also shown as a flow chart in Figure 4.8.

1. Taking the surface as starting point ($L_0$), compute fluid properties at surface conditions and select a length increment ($\Delta L$).

2. Estimate the temperature increment ($\Delta T$) corresponding to the length increment ($\Delta L$).

3. Compute the pressure increment ($\Delta p$) corresponding to the length increment ($\Delta L$) using the pressure gradient equation (Equation 4.29) and flow properties calculated in step 1.

4. Find the average temperature and pressure in the increment.

5. Calculate the fluid and PVT properties at the average temperature and pressure computed in step 4.

6. Compute the pressure gradient ($\Delta p/\Delta L$) in the increment utilizing the fluid and PVT properties obtained at average temperature and pressure determined in step 5 and the pressure gradient equation (Equation 4.29).
7. Find the pressure increment corresponding to the selected length increment, 
\[ \Delta p_1 = \Delta L \left( \frac{\Delta p}{\Delta L} \right) \].

8. Compare the estimated (\(\Delta p_0\)) and calculated (\(\Delta p_1\)) pressure values obtained in step 3 and 7. If they do not meet the given tolerance, consider (\(\Delta p_1\)) as the new pressure increment and go to step 4. Repeats step 4 through 8 until the tolerance value is attained.

9. Repeat the procedure from step 2, using \(p_{i+1} = p_i + \Delta p_1\) as pressure at top of new (\(\Delta L\)) until the sum of \(\Delta L\) equals the total length of the well. Then \(p_{bh} = p_{i-\text{last}} + \Delta p_1\)

Length increment (\(\Delta L\)) is obtained as follows. The program considers a total length of equal well geometry, same wellbore or casing size and same drill pipe or drill collars size, and then it is divided by the number of cells assigned by that section. This is done with the idea to have always an end and a beginning of cell in each change of geometry. In addition, utilizing this criteria interpolation is not required in the last step since the computer program selects the sum of the increments equal to the total depth.

Figure 4.8 Marching algorithm for calculating a pressure traverse

(Figure continued)
i = 0

\[ p_0 = p_s \]

Compute \( \Delta p_0 \) utilizing the pressure gradient equation (Eq. 4.29) and the properties previously calculated

Iter = 0

\[ \bar{p} = p_i + \Delta p_0 / 2 \]

\[ \bar{T} = f(L) \]

Calculate fluid and PVT properties at \( \bar{p} \) and \( \bar{T} \)

Calculate \( \Delta p / \Delta L \)

\[ \Delta p_1 = \Delta L(\Delta p / \Delta L) \]

Check

\[ |\Delta p_0 - \Delta p_1| < \varepsilon \]

Yes

\[ p_{i+1} = p_i + \Delta p_1 \]

\[ i = i + 1 \]

No

\[ \sum \Delta L = L_{\text{Total}} \]

Next time increment

A

B

\[ \Delta p_1 = \Delta p_0 \]

Yes

Iter = Iter +1

No

Check Iter > Limit

Error

Yes
4.1.2 Bullheading Mathematical Model

During the off-bottom blowout control process that is proposed herein, two important stages take place that are linked. The model for each stage was analyzed, built, and programmed independently; then the models were coupled to obtain the final model. The previous section described the model for the dynamic seal and this part will focus on the bullheading model.

Once a dynamic seal is achieved at the injection string depth, the formation fluid can be displaced into an open formation by the kill fluid. This operation is practically a bullheading process. Bullheading is a kill method in which the kill fluid forces the formation fluid back into an open formation. Therefore, a bullheading mathematical model should be developed for the blowout control method proposed herein.

Due to the fact that the available information in the oil industry about the bullheading process is limited, a complete bullheading mathematical model was developed in this dissertation to compute all the kill parameters such as kill rate, kill density, and kill volume. The model also calculates the surface pressure, the pressure and position of the kill fluid - formation fluid interface, and bottomhole pressure, as a function of time during the bullheading process.

The bullheading mathematical model considers three zones during the bullhead process, two in the wellbore below the injection point and one in the reservoir.

Figure 4.9 shows a typical bullheading scenario and the zones used to model the system. Zone 1 represents a permeable formation, into which the formation fluid, either gas, oil, or water, is flowing from the wellbore. Zone 2 is in the wellbore and contains the single-phase formation fluid. Zone 3 is the single-phase kill fluid that is displacing the formation fluid downward.
4.1.2.1 Model Assumptions

The bullheading model assumptions are almost the same as for the dynamic seal model in section 4.1.1.1. The additional considerations in this model are the following:

- A single-phase, gas, oil, or water containing no solids is injected into the formation.
- The injected fluid is flowing outwards radially into the formation.

4.1.2.2 Formation Fluid Removal Efficiency

An extremely important factor in this technique is the efficiency of removal of influx. If a considerable amount of gas remains in the wellbore, the well may unload and blow out again. The reason for poor removal efficiency is that the kill mud bypasses the gas during the displacement operation. It has been found that this phenomenon is dominated by kill fluid velocity.
Koederitz\textsuperscript{35} performed a study of the bullheading process at the LSU Petroleum Engineering Research and Technology Transfer Laboratory. The experiments were conducted in a full-scale, cased well using either water or low viscosity drilling mud as bullheading fluids and gas the formation fluid. A schematic of the research well is shown in Figure 4.10. The main objective of the research was to investigate the removal efficiency, defined as the fraction of gas removed from the wellbore during the operation, for the bullhead method.

![Figure 4.10. Configuration of the research well (after Koederitz\textsuperscript{35})](image)

Casing: 7", 38 lb/ft at 1,994 ft.
Tubing: 2 3/8", 4.7 lb/ft at 1,903 ft.

The general procedure during the experiments was to circulate the well to ensure consistent liquid properties and that no gas was entrained in the system. Then, a known volume of gas was placed at the top of annulus section. The chosen liquid was then pumped at the selected rate downward through the annulus, displacing the gas to the bottom of the well. Simultaneously, all the parameters were monitored. The pumps were stopped and the well shut in. Finally, the removal efficiency was calculated from the initial and final remaining gas volumes in the well.
A total of twelve experimental runs were completed, consisting of seven using water and five using low viscosity mud as the bullheading fluid. Two different bottomhole pressures, 2000 and 3000 psi, were maintained during the experiments. Five pump rates were also utilized, ranging from 12.5 gpm to 50 gpm.

Figure 4.11 shows the removal efficiencies for the experiments as a function of average annular velocity based on the injection rate, with the runs grouped by fluid type and bottomhole pressure.

![Graph showing removal efficiency vs. average annular velocity for different conditions.](image)

Figure 4.11. Removal efficiency (after Koederitz\textsuperscript{35})

It can be seen from the above plot that removal efficiency increases with increasing injection rate. Excellent gas removal is reached at an average velocity of 0.35 ft/sec with low-viscosity mud and 0.7 ft/sec with water. Also it is possible to note that bottomhole pressure value does not substantially affect the removal efficiency once the optimum average velocity is attained.
Koederitz\textsuperscript{35} also computed the bubble rise velocities, the velocity difference between the gas and liquid phase. Those velocities were calculated using the Harmathy equation.\textsuperscript{47} Figure 4.12 shows the calculated bubble rise velocity as a function of annular velocity. Gas and liquid velocities are defined as positive in the downward direction.

Figure 4.12. Gas bubble rise velocities (after Koederitz\textsuperscript{35})

Figure 4.12 shows that the bubble rise velocity tends to be positive as the injection rate increases. Once the average downward water velocity of 0.7 ft/sec is reached, the gas bubble rise velocity becomes essentially zero, and therefore the gas will go down at the same velocity as the kill fluid.

Figure 4.13 presents the removal efficiencies for the experimental runs plotted versus the calculated gas bubble rise velocity. Note that gas bubble rise velocity is positively correlated with removal efficiency. And a complete removal
of gas occurred as gas bubble rise velocities approach zero. In other words, when the water reaches an average downward velocity of 0.7 ft/sec, the gas is completely removed or displaced from the wellbore by water. This indicates that the gas as a whole is flowing downward with the bullheading fluid.

![Graph showing the relationship between bubble rise velocity and removal efficiency](image)

Figure 4.13. Relationship between bubble rise velocity and removal efficiency
(after Koederitz\textsuperscript{35})

Koederitz\textsuperscript{35} also used a multiple regression analysis to develop a predictive method for removal efficiency during bullheading operations. The best-fit model found for the removal efficiency ($R^2 = 0.8872$) contained only two of the dependent variables (fluid type and injection rate). It can be seen in Figure 4.11 that the bottomhole pressure has an insignificant effect in the removal of gas. Hence it was neglected in the model. The resulting model was the following:
Where: 

\[ RE = -161.4 + 75.9 \cdot FL + 271.3 \cdot IVEL \]

**Where:**

- \( RE \) = Removal efficiency, %.
- \( FL \) = Injection fluid type, 1 for water and 2 for mud.
- \( IVEL \) = Injection velocity, ft/sec.

### 4.1.2.3 Mathematical Derivation

A bullheading model has been developed in this dissertation to predict and understand the bullheading process. In addition, the required kill parameters for effective bullheading such as kill density, kill rate, kill fluid volume, bottomhole pressure, surface pressure, interface pressure and position, and gas rate flowing into the formation can be computed as function of time using the model.

The mathematical model takes into account the compression of the formation fluid, which is assumed to behave as a gas, by a known volume of an incompressible kill fluid, as well as the flow of the formation fluid from the wellbore into an open formation. It also considers frictional and hydrostatic pressures for both formation gas and kill fluid in the wellbore.

The general scenario of a bullheading operation is presented in Figure 4.9. It can be seen that before the operation starts, the well is filled with gas. Then kill fluid is pumped into the well, compressing and reducing the gas volume so pressure at the bottom is increasing from both gas compression due to volume reduction and liquid column accumulation. The liquid pumping proceeds until eventually the formation pressure of a permeable zone is reached. At this moment, the bottomhole pressure has reached the injection pressure for that formation and a reservoir model is then included in the process, since there will be flow from the wellbore into whichever open formation's injection pressure has been reached. This flow rate will depend on the formation and formation fluid properties as well as the bottomhole pressure. As the pumping operations continue, the gas is displaced into the formation and the surface pressure simultaneously decreases. The process is completed when all the formation gas...
is displaced into the open formations and the hydrostatic pressure of the kill fluid is enough to balance or exceed the formation pressure.

It has already been noted that when the formation fluid is gas, compressibility must be considered. The isothermal gas compressibility differential equation, which relates the change in volume and pressure due to gas compressibility for an initial gas volume is used. The gas compressibility equation \(^{65}\) is mathematically represented by

\[
\frac{dp}{dV} = \frac{1}{V_i \cdot c_g} \quad (4.46)
\]

Equation 4.46 describes the change in pressure \(dp\) that the gas undergoes as the volume changes \(dV\), which is basically what happens in a bullhead operation as the initial gas volume \(V_i\) is compressed. Therefore, the gas compressibility \(c_g\) plays an important role during this process.

The change in volume \(dV\) is given by the difference between the volume of kill fluid pumped into the well \(V_{kf}\) and the volume of gas that has flowed into an open formation \(V_g\). This is analytically given by

\[
dV = V_{kf} - V_g \quad (4.47)
\]

In order to introduce time in the process, this volume can also be related to the difference between the kill fluid rate, \(q_{kb}\), that is pumped into the well and the gas \(q_{gb}\), that is flowing into the formation over the period of one time step. This relation is

\[
dV = (q_{kb} - q_{gb}) dt \quad (4.48)
\]
Substituting Equation 4.48 in Equation 4.46

\[ \frac{dp}{dt} = \frac{(q_{kb} - q_{gb})}{V_i \cdot c_g} \]  (4.49)

Equation 4.49 requires a mathematical expression to model the gas flow into the formation as a function of time. Therefore, in this work, the unsteady state flow equation in an infinite-acting reservoir will be utilized\(^{24,64}\). It is given by

\[ p_R - p = \frac{162.6q_{gb}B_g \mu_g}{kh} \left[ \log \left( \frac{kt}{\phi \mu_g c_i r_w^2} \right) - 3.23 \right] \]  (4.50)

Due to the fact that in this process the flow rate \( q_{gb} \) is considered positive when the flow is from the wellbore to the reservoir, the above equation becomes

\[ p - p_R = \frac{162.6q_{gb}B_g \mu_g}{kh} \left[ \log \left( \frac{kt}{\phi \mu_g c_i r_w^2} \right) - 3.23 \right] \]  (4.51)

Rearranging the above equation

\[ q_{gb} = \frac{kh(p - p_R)}{162.6B_g \mu_g \left[ \log \left( \frac{kt}{\phi \mu_g c_i r_w^2} \right) - 3.23 \right]} \]  (4.52)

Equation 4.52 represents the unsteady state flow in an infinite-acting reservoir. The gas properties \( B_g, R_b/Mscf \) and \( \mu_g \) are evaluated at the reservoir pressure \( p_R \) and the reservoir properties such as permeability \( k \), porosity \( \phi \), total compressibility \( c_i \), thickness \( h \) and wellbore radius \( r_w \) are considered constant during the process. Therefore, the only time dependent
variables are the flowing bottomhole pressure \( p(t) \) and time \( t \). Therefore, equation 4.52 can be represented as follows

\[
q_{gb} = C(t)(p(t) - p_R) \tag{4.53}
\]

Substituting Eq. 4.52 and 4.53 in Eq. 4.49:

\[
\frac{dp}{dt} = \frac{q_{gb} - C(t)(p(t) - p_R)}{V_i \cdot c_g} \tag{4.54}
\]

Rearranging Eq. 4.54:

\[
\frac{dp}{dt} = \frac{q_{gb} - C(t)p(t) + C(t)p_R}{V_i \cdot c_g} \tag{4.55}
\]

The above differential equation represents the bottomhole pressure change as a function of time during a bullheading operation. It was solved, utilizing the power series method, and the solution is given by

\[
p(t) = p(0) + \frac{q_{gb} - C(t)p(0) + C(t)p_R}{V_i c_g} t - \frac{1}{2} \frac{C(t)(q_{gb} - C(t)p(0) + C(t)p_R)}{V_i^2 c_g^2} t^2
\]

\[
+ \frac{1}{6} \frac{C(t)^2(q_{gb} - C(t)p(0) + C(t)p_R)}{V_i^3 c_g^3} t^3 - \frac{1}{24} \frac{C(t)^3(q_{gb} - C(t)p(0) + C(t)p_R)}{V_i^4 c_g^4} t^4
\]

\[
+ \frac{1}{120} \frac{C(t)^4(q_{gb} - C(t)p(0) + C(t)p_R)}{V_i^5 c_g^5} t^5 - \frac{1}{720} \frac{C(t)^5(q_{gb} - C(t)p(0) + C(t)p_R)}{V_i^6 c_g^6} t^6
\]

\[
+ \frac{1}{5040} \frac{C(t)^6(q_{gb} - C(t)p(0) + C(t)p_R)}{V_i^7 c_g^7} t^7 - + \cdots + \frac{1}{n!} \frac{C(t)^n(q_{gb} - C(t)p(0) + C(t)p_R)}{V_i^n c_g^n} t^n \tag{4.56}
\]
Here \( p(t) \) represents the flowing bottomhole pressure at time \( t \), \( p(0) \) is the pressure at time zero, and \( C(t) \) is the gas flow rate into the productive zone per psi of pressure difference, called in this work "flow coefficient", it is represented by

\[
C(t) = \frac{q_{gb}}{(p - p_s)} = \frac{kh}{162.6 B_g \mu_g} \left[ \log \left( \frac{kt}{\phi \mu_g c_r w^2} \right) - 3.23 \right]
\]

(4.57)

The flow coefficient \( C(t) \) is changing constantly since it depends on time. The time \( t \) is the time since injection of formation fluids began. It is calculated utilizing the time at the previous step plus \( \Delta t \), which is the selected time increment or time step. Note that this time is only a portion of the total time for the overall kill process because it only begins when the dynamic seal is achieved. Several time steps from 10 to 60 sec were used to analyze the results given by the above equations. It can be concluded that the results for the bullheading period are not affected by the time step size since in all the cases they were the same.

4.1.2.4 Global Solution Procedure

Equation 4.56 gives the bottomhole pressure as a function of time during a bullheading operation, but in order to solve the equation, the flow coefficient \( (C) \) and the gas compressibility \( (c_g) \) should be estimated.

Once the time step \( (\Delta t) \) is defined, the gas properties \( (B_g, \text{RB/Mscf} \) and \( \mu_g) \) in Equation 4.57 can be calculated utilizing Equations 4.27 and 4.25, respectively. Therefore, the flow coefficient \( (C) \) can be calculated.

On the other hand, the gas compressibility \( (c_g) \) in Eq. 4.56 is calculated for each time step utilizing the Mattar, Brar, and Aziz expression20:
\[ c_g = \frac{c_r}{p_{pc}} \quad \text{And} \quad c_r = \frac{1}{p_{pr}} \left( \frac{\partial z}{\partial \rho_r} \right)_{T_{pr}} \left[ \frac{0.27}{z^2 T_{pr}} \left( \frac{\partial z}{\partial \rho_r} \right)_{T_{pr}} \right] \quad (4.58) \]

where:

\[
\left( \frac{\partial z}{\partial \rho_r} \right)_{T_{pr}} = \left( A_t + \frac{A_2}{T_{pr}} + \frac{A_3}{T_{pr}^2} + \frac{A_4}{T_{pr}^3} + \frac{A_5}{T_{pr}^4} \right) \left( A_6 + \frac{A_7}{T_{pr}} + \frac{A_8}{T_{pr}^2} \right) \rho_{pr}^2
- 5A_9 \left( \frac{A_2}{T_{pr}} + \frac{A_3}{T_{pr}^2} \right) \rho_{pr}^4 + \frac{2A_{10} \rho_r}{T_{pr}} \left[ 1 + A_{11} \rho_r^2 - \left( A_{11} \rho_r^2 \right)^2 \right] \exp \left( -A_{11} \rho_r^2 \right)
\]

\[ \rho_{pr} = 0.27 \left( \frac{p_{pr}}{z T_{pr}} \right) \]

\[ p_{pc} = 756.8 - 131 \gamma_g - 3.6 \gamma_g^2 \]

\[ p_{pr} = \frac{p}{756.8 - 131 \gamma_g - 3.6 \gamma_g^2} \]

\[ T_{pr} = \frac{T}{169.2 + 349.5 \gamma_g - 74 \gamma_g^2} \]

The constants \( A_1 - A_{11} \) are shown below.

\[
A_1 = 0.3265 \quad A_5 = -0.05165 \quad A_9 = 0.1056
A_2 = -1.0700 \quad A_6 = 0.5475 \quad A_{10} = 0.6124
A_3 = -0.5339 \quad A_7 = -0.7361 \quad A_{11} = 0.7210
A_4 = 0.01569 \quad A_8 = 0.1874
\]

Then, utilizing the selected time step, the computed flow coefficient \( C \) and the gas compressibility \( c_g \), the bottomhole pressure can be estimated utilizing Equation 4.56 as a function of time.
Once the bottomhole pressure is known, it is possible to compute the pressure profile (bottom up) along the formation gas from the bottom to the kill fluid - formation gas interface utilizing the Cullender and Smith equation \(^{21}\), which is given by

\[
\begin{align*}
\frac{1,000 \gamma_g L}{53.356} = \int_{p_{sh}}^{p_{ws}} \frac{ \left( \frac{p}{T_z} \right) }{dp} \, dp \\
0.667 f_q g_{sc} \frac{d^2}{d^3} + \frac{1}{1,000} \frac{H}{L} \left( \frac{p}{T_z} \right)^2
\end{align*}
\]

Equation 4.59 considers the change in the pressure gradient due to friction and due to hydrostatic head of the gas.

After that, the pressure from the interface to the injection string depth is computed utilizing the following equation:

\[
P_{sd} = p_{interface} - (\Delta p_{sf})_s
\]

where:

\[
(\Delta p_{sf})_s = (\Delta p_{sf})_{id} - (\Delta p_{sf})_f
\]

The change in pressure due to frictional pressure losses of the kill fluid is given by

\[
\left( \frac{dp}{dL} \right)_f = \frac{f p_{sf} v_{sf}^2}{772.17d}
\]

And \( (\Delta p_{sf})_f = \left( \frac{dp}{dL} \right)_f \Delta L_{sf} \)

And the change in pressure due to elevation of the kill fluid is represented by
\[
\left( \frac{dp}{dL} \right)_{el} = \frac{\rho_{sf}}{144}
\]  \hspace{1cm} (4.63)

And \[
\left( \Delta p_{sf} \right)_{el} = \left( \frac{dp}{dL} \right)_{el} \Delta L_{sf}
\]

The friction factor \( f \) is calculated utilizing Equation 4.10 for a Newtonian kill fluid or Equation 4.18 for a non-Newtonian kill fluid. The kill fluid velocity is obtained using the Equation 4.34.

### 4.1.2.5. Field Case Application

The bullheading model was applied to a field test reported by Oudeman\(^{46}\). The investigation was conducted to determine how to avoid the possibility that the kill fluid bypasses the gas, causing damage to the productive formation during bullheading operations. The pressure and temperature at the bottom of the hole and at the surface, as well as pump rate and pump pressure, were measured during the test. The scenario of the test is presented in Figure 4.14

**Figure 4.14.** Bullheading conditions given by Oudeman\(^{46}\)
Figure 4.15 shows the both the measured data and the calculated parameters utilizing the bullheading model described herein. The triangles represent the measured data. The circles stand by the calculated parameters. It can be seen that both the calculated bottomhole and surface pressures have good agreement with the measured values.

Figure 4.15 Measured versus calculated parameters for the field test described by Oudeman\textsuperscript{46}
CHAPTER 5

DYNAMIC SEAL - BULLHEADING PROGRAM AND APPLICATIONS

The two models, dynamic seal and bullheading that were defined, developed, and programmed separately in the previous chapters were coupled to obtain the proposed model for "dynamic seal - bullheading". Then, it was implemented in a computer program to assist in off-bottom blowout control analysis and design. In addition, the computer program may be employed to investigate different control options including kill fluid type and properties, injection string geometry and depth, and pump rates, as well as different formation fluid and rock properties. This capability can be used to help determine the most appropriate kill approach for a given set of conditions.

The computer program also includes the conventional off-bottom dynamic kill model, which is based on the steady state analysis approach and considers that only formation fluid exists below the injection point. Consequently, the dynamic method and the proposed method can be compared for the same type of blowout with identical wellbore conditions and reservoir characteristics.

5.1 Computer Program for the Proposed Method

A computer program was developed to implement the global solution procedure discussed in Chapter 4. The results are presented numerically and graphically. The program is divided in three modules, the first one contains the code for the reservoir inflow performance and the dynamic seal models, the second module computes the bullheading process, and the last one performs the gas flow calculations for the wellbore hydraulic performance. A flow chart of the procedure is presented in Figure 5.1
Collect the blowout data

Determine the reservoir fluid properties

Compute the IPR

Compute the WHP when only gas is flowing

Determine the gas flow rate and FBHP

Plot the flowing pressure profile

Select a kill density enough to balance the formation pressure in static conditions

Select a kill flow rate

Does the kill rate reach the dynamic seal

Yes

Estimate the minimum rate to achieve at least a velocity of 0.7 ft/sec below the injection depth

Estimate the minimum rate for dynamic seal - bullheading kill

Does the pumping system have capacity to pump the rate selected

Yes

Calculate and plot the pressure profile versus time for a critical point
(Casing shoe, lost circulation zone, or weak point in the casing)

Does the critical point Support the maximum pressure imposed for those flow conditions

Yes

No

Increases string depth. Otherwise consider another control technique (off-bottom dynamic kill, capping, relief well)

No

Increase kill flow rate

No

Yes

Increases string depth or obtain another pumping system. Otherwise consider another control technique (off-bottom dynamic kill, capping, relief well)

A

B

Figure 5.1 Algorithm to estimate the dynamic seal - bullheading kill parameters

(Figure continued)
The program is composed of several work sheets that are linked within an Excel file. The following section will briefly explain the main characteristics of each sheet.

**Data Sheet**  The data sheet includes the required data to analyze an off-bottom blowout. It also schematically displays the wellbore geometry and a summary of the conditions in the well being analyzed.

**IPR Sheet**  This part of the program presents a table of the calculated reservoir inflow performance utilizing several gas flow rates. The table shows the flowing bottomhole pressure for each given gas formation rate.

**WHP Sheet**  This sheet is a table of the calculated wellbore hydraulic performance for different gas flow rates. The gas rates are the same as those utilized in the reservoir inflow performance calculation.

**Gas Flow Rate Determination Plot**  This sheet plots the previously calculated IPR and WHP. The intersection of these curves gives the gas flow rate after the well has been completely unloaded of all the liquid and only formation gas is flowing in the system.
**Pressure Profile Sheet** This sheet is a table of the pressure profile generated by the formation gas flowing through the well. The pressure values are given for several depths in the well.

**Pressure Profile Plot** This sheet plots the previously calculated pressure profile as function of depth and presents the pressure behavior from the bottom of the well to the surface when only gas is flowing in the wellbore.

**Gas Properties Sheet** The gas properties sheet displays the properties of the gas throughout the wellbore for the flow conditions previously obtained, which are used as the initial conditions of the control process.

**Dynamic Seal Control Sheet** This segment of the program presents the process and flow conditions to reach the dynamic seal. After the kill fluid properties are input, the flow conditions as function of time are presented in a table. Also the most important parameters such as time, gas flow rate, bottomhole pressure, injection depth pressure, surface pressure, and the pressure at any critical point in the well during the dynamic seal process are summarized and displayed.

**Bullheading Control Sheet** This sheet presents the well and flow conditions during the bullheading process after the dynamic seal has been reached. The program uses the same kill fluid properties as employed in the dynamic seal model. The parameters such as interface pressure and position, bottomhole pressure, injection string pressure, surface pressure, and gas rate flowing into the formation are shown as function of time.

**Results Sheet** The results sheet summarizes the fluid properties and kill parameters for a given set of input variables that are being evaluated for possibly controlling an off-bottom blowout utilizing this concept. It also shows a prediction of the bottomhole pressure, injection depth pressure, gas flow rate, and pressure at any critical point in the well as function of time during the whole control process.
**Bottomhole Pressure Plot**  This sheet plots the bottomhole pressure as function of time during the whole control operation.

**Surface Pressure Plot**  This sheet presents a graph of the predicted surface pressure as function of time during the pumping operation.

**Plot of the pressure at any depth of interest**  This plot displays the pressure at any depth of interest as function of time. It can be used to predict the pressure behavior at any critical spot in the well, such as the casing shoe, a lost circulation zone, a low-pressure formation, or a weak spot in the casing.

**Gas Flow Rate Plot**  This section displays a plot versus time of the gas flow rate from the reservoir to the wellbore during the dynamic seal generation and from the wellbore to the reservoir during the bullheading process.

**Dynamic Kill Sheet**  The dynamic kill sheet presents the analysis of a possible blowout control employing the conventional dynamic method. This model takes exactly the same well and reservoir data that were input in the data sheet as well as the same kill fluid characteristics utilized by the proposed method. This allows a meaningful comparison between the two methods.

**Dynamic Kill Plot**  This sheet presents the plot of the dynamic kill analysis and can be used to select an appropriate kill fluid rate and properties to control the blowout utilizing this concept.

The various sheets that provide plots as function of time give a prediction of the blowout control process that can be helpful for selecting parameters for a better kill job.

**5.1.1 Input Data**

Table 5.1 presents the required data to run the program. It also shows the respective units for each variable.
Table 5.1 Input data required by the computer program

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wellbore Data</strong></td>
<td></td>
</tr>
<tr>
<td><em>First Casing</em></td>
<td></td>
</tr>
<tr>
<td>Outside Diameter</td>
<td>Inches</td>
</tr>
<tr>
<td>Inside Diameter</td>
<td>Inches</td>
</tr>
<tr>
<td>Depth</td>
<td>Feet</td>
</tr>
<tr>
<td><em>Second Casing (Liner)</em></td>
<td></td>
</tr>
<tr>
<td>Outside Diameter</td>
<td>Inches</td>
</tr>
<tr>
<td>Inside Diameter</td>
<td>Inches</td>
</tr>
<tr>
<td>Depth</td>
<td>Feet</td>
</tr>
<tr>
<td>Top Liner Depth</td>
<td>Feet</td>
</tr>
<tr>
<td><em>Injection string (first geometry)</em></td>
<td></td>
</tr>
<tr>
<td>Outside Diameter</td>
<td>Inches</td>
</tr>
<tr>
<td>Inside Diameter</td>
<td>Inches</td>
</tr>
<tr>
<td>Depth</td>
<td>Feet</td>
</tr>
<tr>
<td><em>Injection string (second geometry)</em></td>
<td></td>
</tr>
<tr>
<td>Outside Diameter</td>
<td>Inches</td>
</tr>
<tr>
<td>Inside Diameter</td>
<td>Inches</td>
</tr>
<tr>
<td>Length</td>
<td>Feet</td>
</tr>
<tr>
<td>Absolute roughness</td>
<td>Inches</td>
</tr>
<tr>
<td><em>Open hole</em></td>
<td></td>
</tr>
<tr>
<td>Total well depth</td>
<td>Feet</td>
</tr>
<tr>
<td>Bit diameter</td>
<td>Inches</td>
</tr>
<tr>
<td><strong>Reservoir Data</strong></td>
<td></td>
</tr>
<tr>
<td>Reservoir pressure</td>
<td>Psi</td>
</tr>
<tr>
<td>Reservoir temperature</td>
<td>°F</td>
</tr>
<tr>
<td>Surface gas temperature</td>
<td>°F</td>
</tr>
<tr>
<td>Gas specific gravity (air = 1.0)</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>Permeability</td>
<td>md</td>
</tr>
</tbody>
</table>

(Table continued)
5.1.2 Potential Applications of the Program

The computer program described in this chapter can be utilized to analyze the following surface and underground blowout control processes:

- Off-bottom dynamic seal - bullheading kill
- On and off-bottom In well dynamic kill
- Relief well dynamic kill
- Bullheading operations

The input data can be adapted to evaluate off-bottom blowout control during drilling, completion, workover or production operations. The injection string may be a drill string including drill pipe and drill collars, casing, tubing, work string, coil tubing, any other tubular, or the annulus between the inner string and an outer casing or open hole.

The program also may help to develop a sensitivity analysis and investigate how the many parameters that affect the off-bottom blowout control design and the kill process. In particular, the potential of the well regaining
control using the pumping units and control fluid available on the rig site can be evaluated to determine whether more equipment and material would be required. Alternative kill string geometry and depth can be evaluated for snubbing or stripping operations. These analyses can consider different kill fluid rate, density and viscosity, and injection string geometry and depth by changing the input data.

5.1.2.1 Specific Applications of the Method

Due to the fact that this is a high rate procedure, high pressures are likely to be generated in the system. Therefore, the method may not be applicable for surface blowouts when a long openhole interval is present, since an underground blowout may be generated, possibly worsening the problem. However, there are various scenarios in which this procedure can be very advantageous.

Figure 5.2 Potential application of the proposed method during drilling operations
During drilling, a likely application for this method is when the well blows out from a formation with a limited amount of open hole above the formation and the drill string off-bottom. This scenario would potentially apply when intermediate casing was set above an overpressured reservoir. Figure 5.2 shows schematically this scenario.

Another likely application is to a blowout during completion or workover operations, since most wells are cased and then perforated during the completion stage. Thus the proposed method can be employed in those wells if a blowout takes place with the tubing distant from the bottom. Figure 5.3 displays schematically this scenario.

Figure 5.3 Potential application of the proposed method during completion or workover operations
5.2 Results of the Applications

The mathematical models outlined in Chapter 4 and the computer program described in this chapter provide a means to analyze and design an off-bottom blowout control applying the dynamic seal-bullheading concept proposed in this dissertation.

The following section presents the design and analysis of two different off-bottom blowout scenarios utilizing this concept. Then the same blowouts will be analyzed utilizing the dynamic kill method. The results will be compared and discussed. The first is an actual field case and the second is a hypothetical off-bottom blowout with input data from a real well configuration and reservoir.

For the computer run, the bottomhole pressure, surface pressure, gas flow rate during the control and kill parameters are displayed as function of time. Based on those plots, an analysis has been performed.

The analysis provides an improved understanding of the dynamic seal-bullheading concept that can be useful in evaluating, planning, and conducting off-bottom blowout control operations.

5.2.1 Post-analysis of an Actual Field Case

This field case is for an off-bottom underground blowout that occurred during a trip in the hole in a deep gas well. The drill string became stuck at more than 2,000 ft above total depth, and due to the previous history and excessive surface pressures, it was concluded that an underground blowout was in progress.

Noise logs were run in the drillpipe, which confirmed flow from the objective sand to the casing shoe (Smith et al.). The blowout data and scenario is presented in Figure 5.4.
The formation fluid path is through the openhole from the bottom of the hole to the injection string. Then, it is through the annual section between the drillstring and wellbore from the injection string depth to the 9 5/8" casing shoe.

5.2.1.1 Actual Kill Operations

The actual kill operation was performed utilizing the dynamic kill concept. It began by pumping 13.5 ppg mud at 3 bpm and staging up to 17 bpm. The initial pump pressure at 17 bpm was 6000psi. As mud began to fill the annulus,
this pressure increased to 6,900 psi. A steady state condition of 6,800 psi at 16.3 bpm was achieved after pumping about 700 barrels.

Circulation continued for another 1000 barrels to help remove some of the remaining gas from the openhole and annulus. Then 1000 barrels of 15.5 ppg were pumped at a final rate and pressure of 14 bpm and 5,350 psi to provide additional overbalance. The 13.5 ppg mud weight from the injection depth back to the surface gives a bottomhole pressure adequate to overbalance the formation pressure. However, additional overbalance was desired to offset potential loss of hydrostatic pressure when gas from below the injection depth migrates upward into the annulus around the pipe (Smith et al.\textsuperscript{70}). The actual kill parameters are presented in Table 5.2

Table 5.2 Actual kill parameters for the field case

<table>
<thead>
<tr>
<th>Kill parameters utilized for controlling the well</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kill flow rate</td>
<td>17 bpm</td>
</tr>
<tr>
<td>Kill fluid density</td>
<td>13.5 ppg (101 lbm/ft\textsuperscript{3})</td>
</tr>
<tr>
<td>Kill time</td>
<td>6,000 seconds (100 min)</td>
</tr>
<tr>
<td>Kill volume (13.5 ppg fluid)</td>
<td>1,700 bbl</td>
</tr>
<tr>
<td>Maximum peak pressure</td>
<td>6,900 psi</td>
</tr>
<tr>
<td>Maximum HHP</td>
<td>2,874</td>
</tr>
</tbody>
</table>

The proposed model was applied to simulate the kill performed in this field case and to compare the simulation results to the actual results. The models were then used to simulate both a dynamic seal - bullheading kill and a conventional off - bottom dynamic kill. The results of these are then compared to the actual case and the differences are discussed.

5.2.1.2 Simulation of Actual Case

The computer program was utilized to simulate the real well conditions during the control for different pump rates and kill fluid densities utilized after the
steady state conditions were reached. First, a 13.5-ppg fluid and a rate of 17 bpm were used, which reached a pump pressure of 6,900 psi. Then, they reduced the rate at 16.3 bpm obtaining a constant pressure of 6,800 psi. Finally, they switched to 15.5 ppg fluid and a rate of 14 bpm, which reduced the pump pressure at 5,350 psi.

The computer program employed these flow conditions to compute the surface pressure considering that the steady state conditions were attained. Table 5.3 presents the actual surface pressures recorded during the control as well as the ones given by the program. It can be seen that the pressures predicted by the program have good agreement with the ones measured during the control.

Table 5.3 Actual and calculated surface pressures for the field case

<table>
<thead>
<tr>
<th>Flow conditions</th>
<th>Surface pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kill flow rate</td>
<td>Kill density</td>
</tr>
<tr>
<td>17 bpm</td>
<td>13.5 ppg</td>
</tr>
<tr>
<td>16.3 bpm</td>
<td>13.5 ppg</td>
</tr>
<tr>
<td>14 bpm</td>
<td>15.5 ppg</td>
</tr>
</tbody>
</table>

5.2.1.3 Dynamic Seal - Bullheading Kill

The proposed method anticipates using only one kill fluid density during the whole control process, which is selected to balance or overbalance the reservoir pressure in static conditions. Although only a 12 ppg fluid is required to fulfill this requirement, a kill fluid density of 13.5 ppg (101 lbm/ft³) was selected to be consistent with the real control operations and obtain a meaningful comparison to the other cases. The kill parameters and predictions given by the proposed method are the followings.
Kill parameters

The kill parameters suggested by the proposed method are presented in the Table 5.4.

Table 5.4 Suggested kill parameters for the dynamic seal - bullheading method

<table>
<thead>
<tr>
<th>Kill parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kill flow rate</td>
<td>18.8 bpm</td>
</tr>
<tr>
<td>Kill fluid density</td>
<td>13.5 ppg (101 lbm/ft³)</td>
</tr>
<tr>
<td>Kill time</td>
<td>5,000 seconds (83 min)</td>
</tr>
<tr>
<td>Kill volume</td>
<td>1,560 bbl</td>
</tr>
<tr>
<td>Maximum peak pressure</td>
<td>6,961 psi</td>
</tr>
<tr>
<td>Maximum HHP</td>
<td>3,207</td>
</tr>
</tbody>
</table>

The recommended kill density to control the off-bottom underground blowout is 13.5 ppg (101 lbm/ft³) which is adequate to support the formation pressure in static conditions. Once the kill density is defined, the kill rate is founded performing several simulations at higher rates until obtaining one that fulfills both models dynamic seal and bullheading. The recommended kill rate to generate the dynamic seal and then displace the formation gas into the formation is about 18.8 bpm. The time to regain control of the well utilizing these kill conditions is about 5,000 seconds (83 minutes).

Bottomhole pressure

The model computes the profile of the bottomhole pressure as a function of time during the entire control process. This behavior is shown in Figure 5.5. It can be seen in Figure 5.5 that after the pumping operations start, the pressure begins to increase due to the flow of kill fluid in the annular section. This causes an increase in both frictional and hydrostatic pressure. Then, the injection pressure is reached and the gas is displaced into the formation. The boundary condition utilized in this calculation was the pressure at 9 5/8" casing shoe. It was
estimated by the operator to be 10,388 psi. And it was obtained utilizing the hydrostatic pressure given by the 13.5 ppg mud from the surface to the casing shoe depth plus the surface casing pressure.

Figure 5.5 Bottomhole pressure given by the dynamic seal - bullheading method

Surface Pressure

The surface pressure profile as a function of time given by the model is presented in Figure 5.6. The pressure begins to increase as the kill fluid is being pumped into the well due to the friction drop caused by the fluid in both drillstring and annular section. Then a maximum value is reached when gas flow has nearly stopped and only liquid is flowing from the injection point to the casing.
shoe. The pressure then decreases due to the fact that the gas is displaced into the formation and the hydrostatic pressure provided by the kill fluid below the injection string helps to overcome the formation pressure.

Figure 5.6 Surface pressure given by the dynamic seal - bullheading method

Pressure profile at dynamic conditions

An important recommendation about this method is that it may not be applicable when a long openhole interval exists. The high rates and therefore high wellbore pressures that are expected, when using this method could simply force the flow to another loss zone potentially loosing the opportunity to regain
the control of the well utilizing a lower rate method\cite{63}. Nevertheless, during the analysis of this field case, it was found that the method could be applied when long openhole interval is present as long as the pressures generated within the wellbore during the process do not reach the fracture pressure of an exposed formation below the injection point. Figure 5.7 shows the pressure profile from the casing shoe to the bottom of the well at dynamic conditions. It also presents the fracture pressure of the exposed formations. It can be seen that the fracture conditions are only reached at the casing shoe, hence this method is reliably applied to this case.

![Figure 5.7 Pressure profile at dynamic conditions during the simulation](image-url)
5.2.1.4 Conventional Off - Bottom Dynamic Kill

The field case was also analyzed utilizing the conventional dynamic kill model. Again a kill fluid density of 13.5 ppg (101 lbm/ft³) was used to obtain a significant comparison with the dynamic seal - bullheading method. A conventional dynamic kill analysis, which considers only formation fluid to be present below the injection point, for the field case is presented in Figure 5.8.

Figure 5.8 Off - bottom conventional dynamic kill analysis
It can be seen in Figure 5.8 that the dashed line representing wellbore hydraulic performance curve always results in a bottomhole pressure greater than the reservoir IPR curve showed as a solid line when 15 bpm of 13.5 ppg fluid is pumped in the system. Therefore, the required flow rate for regaining the control of the well is about 15 bpm. The system analysis approach plot also shows that the system is a hydrostatic dominated one. The kill parameters give by the dynamic method are presented in Table 5.5

Table 5.5 Dynamic kill parameters

<table>
<thead>
<tr>
<th>Kill parameters given by the dynamic kill method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kill flow rate</td>
</tr>
<tr>
<td>Kill fluid density</td>
</tr>
<tr>
<td>Maximum peak pressure</td>
</tr>
<tr>
<td>Maximum HHP</td>
</tr>
</tbody>
</table>

The 15 bpm were found by calculating the wellbore hydraulics performance curve utilizing the selected kill fluid density and several kill rates. The kill rate chosen was the one that builds the WHP that is just above of the IPR.

5.2.1.5 Comparison of the Methods

A considerable advantage of the proposed method is that it utilizes only one kill density during the whole control process, which avoids additional operations to change from lighter to heavier density. Also a faster and more positive kill is performed since the formation fluid is forced in to the producing sand and the well completely filled with the kill density. The control of the actual field case performed an additional operation to change the fluid density, since the control plan considered only formation fluid below the drillstring. Hence a higher density would be required from the injection depth to the casing shoe to offset
potential loss of hydrostatic pressure when gas from below the injection depth migrates upward into the annulus.

On the other hand, the kill rate and the peak pressure calculated by the dynamic method is lower, so less HHP would be required to perform the control.

5.2.2 Hypothetical Case

A hypothetical off-bottom blowout was also analyzed utilizing both the dynamic seal-bullheading concept and the dynamic kill method. The results will be compared and discussed.

Figure 5.9 Hypothetical off-bottom blowout input data and scenario
The conditions for the hypothetical blowout were taken from a real well configuration and reservoir. Figure 5.9 shows the input data and the off-bottom blowout scenario that was considered for the analysis.

The control was calculated considering that the kill fluid was pumped through the injection string. The computer program can also perform the calculations for control fluid that pumped through the annular section if the blowout occurs up the drillstring. In this example, the formation fluid path is from the bottom of the hole until reaches the injection string. Then, the formation gas flows to the atmosphere through the annular section between the drillstring and casings.

5.2.2.1 Dynamic Seal - Bullheading Kill

The proposed method considers use of only one density kill fluid, and it should be enough to maintain the reservoir pressure in static conditions. Therefore, the selected kill fluid was a 15 ppg (112-lbm/ft³) brine, which will generate an overbalance of about 1,000 psi in static conditions. This overbalance is considered due to the well conditions and seriousness of the circumstances since it is not possible to shut the well in just after the blowout is controlled but until the well is secure with the installation or fixing of the surface equipment.

The kill parameters and predictions given by the proposed method follow.

**Kill parameters**

The suggested kill parameters for the proposed method are presented in the Table 5.6. The recommended kill density to control the off-bottom blowout is 15 ppg (112-lbm/ft³), which is adequate to support the formation pressure in static conditions. Once the kill density is defined, the kill rate is found by performing several simulations until obtaining one that fulfills both models, dynamic seal and bullheading, defined in Chapter 4.
Table 5.6 Suggested kill parameters by the proposed method

<table>
<thead>
<tr>
<th>Kill parameters given by the proposed method</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kill flow rate</td>
<td>14</td>
</tr>
<tr>
<td>Kill fluid density</td>
<td>15</td>
</tr>
<tr>
<td>Kill time</td>
<td>1,900 seconds (32 min)</td>
</tr>
<tr>
<td>Kill volume</td>
<td>448 bbl</td>
</tr>
<tr>
<td>Maximum peak pressure</td>
<td>5,300 psi</td>
</tr>
<tr>
<td>Maximum HHP</td>
<td>1,818</td>
</tr>
</tbody>
</table>

The recommended kill rate to generate the dynamic seal and displace the formation gas into the formation is about 14 bpm. The time to control the off-bottom blowout utilizing these kill conditions is about 1,900 seconds (32 minutes).

Gas flow rate determination

The program utilizes the reservoir and wellbore models previously presented to obtain the amount of gas flowing under blowout conditions.

Figure 5.10 displays the gas flow rate determination after the well has unloaded all of the liquid and the free flowing equilibrium conditions have been reached in the system. It plots the bottomhole flowing pressure versus gas flow rate. The solid line stands for the reservoir inflow performance (IPR) and the dashed line represents the wellbore hydraulics performance (WHP).

The intersection of these two lines is the simultaneous solution of the IPR and WHP mathematical models and represents natural flow point of the system for the given well conditions. It also determines the bottomhole flowing pressure and blowout gas flow rate, which are about 15,400 Mscfd and 980 psi respectively.
Figure 5.10 Gas flow rate determination of the hypothetical off-bottom blowout

**Bottomhole pressure**

The program also computes the profile of bottomhole pressure as function of time during the whole control process. This plot is shown in Figure 5.11. It can be seen that after the control begins, the pressure increases due to the friction and hydrostatic pressure of the kill fluid in the annular section. Then, the injection pressure is reached and the formation gas is forced into the formation by the kill fluid, generating an additional increase of the bottom pressure due to the gas compression and due to fact that the lower part of the well is being filled up with the kill mud.
Figure 5.11 Bottomhole pressure during the control process of the hypothetical off-bottom blowout

**Surface pressure**

The model also computes the profile of surface pressure as function of time during the whole control process. This plot is shown in Figure 5.12. The initial surface pressure is given by the static gas in the drill string, which is function of the wellbore hydraulic performance in the well when only formation gas is flowing. After the pumping operations begin the surface pressure increases due to the friction losses of the kill mud in both the injection string and annular section. Then, the injection pressure is reached and the formation gas is
forced into the formation by the kill fluid generating an additional increment of the surface pressure due to the gas compression. After that the pressure starts to decrease because of the hydrostatic column generated below of the injection string helps to overcome the formation pressure. The surface pressure prediction is a very important parameter since it can assist in the selection of the appropriate pumping system and in monitoring whether the actual job is proceeding as expected. Hence, a better kill job may be performed.

Figure 5.12 Surface drillpipe pressure during the control process of the hypothetical off-bottom blowout
Gas flow rate during the control operation

The gas flow rate during the control operation as function of time is another output of the program. This behavior is presented in Figure 5.13. It can be seen that the gas flow rate before to start the pumping operation is about 15,400 Mscfd. After the control operations commence the gas flow rate decreases due to the increasing of the bottomhole pressure caused by the kill fluid flowing in the annular section. Then, the injection pressure is reached and the gas is displaced by the kill fluid into the formation (bullheading process). The increase in the gas rate flowing into the formation is due to the increase in hydrostatic pressure caused by the control fluid.

Figure 5.13 Gas flow rate during the control process of the hypothetical off-bottom blowout
Tables as example of the outputs of the program presenting the bottomhole pressure, surface pressure and gas flow rate as well as the conditions during the bullheading process as function of time for the hypothetical blowout are presented in Appendix C.

5.2.2.2 Conventional Off - Bottom Dynamic Kill

The computer program also contains the dynamic kill model. Therefore, a comparison of the two methods can be made for the same off - bottom blowout with identical wellbore geometry, reservoir properties and type of kill fluid. The dynamic kill method analysis is based on the steady state system analysis approach as presented in Figure 5.14. It shows that if a rate of 5 bpm is pumped the wellbore hydraulics performance curve intersects the reservoir inflow performance curve which means that a stable flow condition results and the reservoir continues producing at a gas flow rate of about 11,500 Mscfd. However if the kill rate is increased to about 9 bpm, the wellbore hydraulics performance curve is practically tangent to and just above the inflow performance curve. This means that at that rate a stable gas lift flow condition would not be possible, and the well would be killed. Thus the minimum kill rate for a conventional dynamic kill is 9 bpm.

The suggested kill parameters for the dynamic kill method are presented in Table 5.7. Since the analysis was performed with the same kill fluid type to make a meaningful comparison, the two methods propose the same kill density and viscosity, which are 15 ppg (112-lbm/ft$^3$) and 20 cp. The recommended kill rate by the dynamic method is about 9 bpm.

Table 5.7 Suggested kill parameters by the dynamic method

<table>
<thead>
<tr>
<th>Kill parameters given by the dynamic kill method</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kill flow rate</td>
<td>8.8 bpm</td>
</tr>
<tr>
<td>Kill fluid density</td>
<td>15 ppg (112 lbm/ft$^3$)</td>
</tr>
<tr>
<td>Maximum peak pressure</td>
<td>4,697 psi</td>
</tr>
<tr>
<td>Maximum HHP</td>
<td>1,102</td>
</tr>
</tbody>
</table>
Figure 5.14 Dynamic kill analysis of the hypothetical off-bottom blowout

The relative advantages of dynamic seal–bullheading and conventional dynamic kill methods can be assessed by comparing the results of the kill parameters and predictions for applying these two methods to the two examples in this chapter. The potential advantages of the dynamic seal–bullheading method are that it requires less mud volume, less time, and lower mud weight,
and provides a more positive kill. The potential advantages of a conventional dynamic kill are that it requires less pump horsepower, less pump rate capacity, and lower surface pressures, and it imposes less pressure on surface and downhole equipment and on potential lost circulation zones.

Examples of these are evident when Table 5.4 is compared with Table 5.2 and Table 5.5, and 5.6 is compared with Table 5.7. As expected, the proposed method requires a higher kill rate since it has to deliver both upward and downward flow rates during the control. The upward rate must maintain the dynamic seal through the annular section between the injection string and the casings, and the downward rate must displace the formation gas into the producing zone. For the actual field case, the required rate for the proposed method was 18.8 bpm versus a minimum of 15 bpm calculated for a conventional dynamic kill. The maximum pump pressure required for the proposed method was 6,961 psi compared to 6,010 psi for the conventional method. The rates and pressure are close for both methods, apparently because pressures in this example are hydrostatic dominated.

The results for the hypothetical case are quite different. The required rate and maximum surface pressure for the proposed method are 14 bpm and 5,300 psi respectively. These are both larger than the 8.8 bpm and 4,697 psi required for a conventional kill. The maximum bottom hole pressure predicted for the proposed method is almost 8,400 psi versus 7,600 psi for conventional control.

Therefore, the proposed method potentially provides a much more rapid kill, but may also require significantly more pump capacity and pressure and poses more risk of pressure related failures both downhole and at the surface.

5.3 Advantages and Disadvantages of the Proposed Method

The overall advantage of the dynamic seal - bullheading procedure compared with the conventional dynamic kill is that the proposed method should provide a more reliable and conclusive off - bottom kill because the formation fluids will be forced back into the formation and the well completely filled with a
kill density fluid. Generally, this means that the well can also be controlled more quickly with a minimal control fluid volume because the method ensures efficient displacement of the blowout fluids into open hole formations. It also should eliminate or minimize the need for further well control operations after the kill is completed.

The dynamic method, on the other hand, does not guarantee that the formation fluid is displaced from the wellbore. It is uncertain whether, and how much, gas remains in the well. Once pumping ceases, any remaining gas will migrate and will tend to unload the well again unless some additional control actions are taken. Possible examples are re-establishing a surface shut in and instituting volumetric control methods, and tripping in the hole in order to circulate out the remaining gas either using conventional well control methods or by circulating at a rate that keeps bottomhole pressure greater than formation pressure.

The proposed method should also provide more reliable kill parameters, because it considers known fluid properties from the surface to the bottom of the well whereas the real conditions below the injection depth are uncertain during conventional dynamic kills.

One example is that the proposed method should define a lower, but more reliable kill density. This results from the proposed method completely filling the well with the control fluid, whereas the conventional dynamic kill can only insure that the length from the injection depth to the surface contains the control fluid. This can require very high kill fluid densities to ensure hydrostatic control. In the hypothetical case, a 15 ppg mud provides an off-bottom dynamic kill at a pump rate of 8.8 bpm. However, a 19.1 ppg mud would be required to ensure hydrostatic control. Under some circumstances, the required density would be impossible to achieve.

Another example is that the required kill volume with the proposed method is defined, whereas the volume that must be pumped to insure a complete kill with the conventional method is uncertain because fluid behavior below the
injection point is uncertain. Therefore, even the sophisticated, commercial, time-based simulators cannot presently give rigorous predictions for off-bottom conditions.

The proposed method involves controlling the well with one fluid density and avoids additional operations to change the control fluid density as is sometimes performed with the conventional dynamic kill. This simplifies both planning and operations, but overrides the possibility of minimizing the surface and subsurface pressures required for control by using low density fluids as envisioned by Blount\textsuperscript{32}.

A related disadvantage of the proposed method is that the higher rates impose higher pressures on surface and downhole equipment and on the open formations. Therefore, the equipment used must have higher pressure ratings and the risk of lost returns, and possibly of an underground blowout, is increased.

The primary advantage of the conventional dynamic kill is that it requires lower rate and therefore, involves lower pressures. A relatively new concept for defining a truly minimum kill rate for off-bottom kills has been described by Flores-Avila et al\textsuperscript{63}. These methods have increased potential to be practical for early implementation using existing rig equipment because the rate and pressure capabilities required are lower than those required by the proposed method.

The preferable method for a specific situation is obviously dependent on the well conditions, equipment capability and availability, and other factors. The methods described herein are intended to provide a quantitative basis for selecting between the dynamic kill and dynamic sea-bullheading methods for any specific situation.
CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A study of the two current, off-bottom, blowout control engineering procedures used in the oil and gas industry has been performed. This research also proposes an alternative engineering design procedure to control off-bottom blowouts. An off-bottom blowout is any blowout where there is not an intact flow path to allow fluids to be injected from the surface to the bottom of the well. The following summary and conclusions were drawn from this investigation. Recommendations are also made for improving the proposed new method.

6.1 Summary

The dynamic and momentum kill are the only currently available methods in the petroleum industry to control off-bottom blowouts by pumping kill fluid through an injection string into the well. In this research, a comprehensive study of these two current engineering concepts was performed, and a thorough review of published historical and hypothetical cases applying these techniques was accomplished. A computer program for each method was built to assist in this analysis. The advantages, important shortcomings, and design problems of each method were identified by this study.

An alternative engineering design procedure to control off-bottom blowouts was also developed. This method is called "dynamic seal - bullheading". It is essentially a combination of the dynamic kill and bullheading concepts. The principle of this method is based on two important stages. First a dynamic seal has to be generated at the injection string depth. And second, a portion of the kill fluid is forced to flow downward below the injection pipe to displace the remaining formation fluid in the wellbore to go back into an open formation. In other words, the procedure is based on achieving a pressure distribution in the system that uses a high pressure gradient from the string depth
to the surface due to the kill flow rate and density to force the well fluids to simultaneously move downward to be injected in an open formation.

A model of this concept was defined and implemented in a computer program that can predict the effect of potential kill parameters such as kill flow rate, kill fluid density, kill fluid volume, pumping time, and effect of control depth. It predicts the formation fluid influx, surface pressure, bottomhole pressure, and pressure at critical points in the well as a function of time for a job using the selected parameters.

The new computer program was utilized on two different off-bottom blowout scenarios to simulate and analyze the control of each. The first is an actual field case and the second is a hypothetical blowout with input data from a real well configuration and reservoir. The same blowouts were also analyzed utilizing the conventional dynamic kill. The results were compared and discussed.

The computer program developed in this work can be utilized to analyze the following surface and underground blowout control processes:

- Off-bottom dynamic seal - bullheading kill
- On and off-bottom dynamic kill
- Relief well dynamic kill
- Bullheading operations

A bullheading mathematical model was required to predict behavior of the well during the bullheading phase of the proposed method. Therefore, a bullheading model was developed in this work to compute the required kill parameters such as kill flow rate, kill density, and kill volume. The model also calculates the surface pressure, interface (kill fluid - formation fluid) pressure and position, and bottom hole pressure as a function of time during the bullheading process.
6.2 Conclusions

6.2.1 Conventional Dynamic Kill Method

The conventional dynamic kill method has been well defined in the literature and widely applied to surface and underground blowouts. The following conclusions have been reached by this study.

1. The conventional dynamic kill method, which is based on the steady state system analysis approach, has been utilized in several off-bottom blowout control operations and is currently the only proven method for these situations.

2. The steady state systems analysis approach was shown to be applicable to all of the field cases analyzed in this study. Consequently, this is a proven method for designing and analyzing off-bottom kills.

3. The kill rates, and consequently the pressures, required for a conventional dynamic kill are lower than for the proposed method. This can be an advantage if there are equipment or subsurface pressure limitations.

4. Some limitations and shortcomings occur when this method is applied to off-bottom conditions, i.e. where the injection string is distant from the bottom of the well. Specifically, the method does not take into account that the kill fluid may fill the wellbore from the injection point to the bottom of the well, and assumes that only formation fluid remains in the part of the wellbore during the control. This assumption requires that the mud density from the injection depth to the surface be sufficient to balance the formation pressure in static conditions with the following consequences.

5. The calculated density may be higher than can practically be achieved. In this case, the opportunity for in-well control would be discarded, and another more expensive or time consuming blowout control methodology such as snubbing in or drilling a relief well would be adopted, potentially unnecessarily.
6. A considerable amount of gas may remain in the section below the injection point. If the circulation rate is reduced or stopped, the gas may start to migrate, expanding, and causing the well to begin to unload again. This possibility typically requires additional procedural steps after achieving an initial dynamic kill.

7. The steady state systems analysis approach cannot precisely determine the optimum kill parameters because of the uncertainty about the real conditions and mixture properties below the injection depth. A specific example is that the total volume of mud required cannot be precisely defined.

6.2.2 Momentum Kill Method

The momentum kill has been described as a method for controlling off-bottom blowouts. Based on both the logical analysis of the concept and specific example calculations for actual kills, it is concluded that the momentum kill design method is irrelevant for controlling blowouts. The field results attributed to momentum kills in published reports can be explained by analyzing these cases as dynamic kills.

6.2.3 Dynamic Seal - Bullheading Kill Method

An alternative concept for off-bottom well control, the dynamic seal – bullheading method, has been defined. It uses a dynamic kill-like procedure to impose a wellbore pressure that is high enough to displace formation fluids into open formations in the well. The following conclusions about this new alternative, developed by combining previous methods, have been reached.

1. The overall advantage of the dynamic seal – bullheading procedure is that it should provide a more reliable and conclusive off-bottom kill because the formation fluids are displaced from the well and replaced with a kill density fluid. Therefore, the risk that any gas will remain below the injection point, which would migrate and tend to unload the well, is minimized.
2. The higher rates used and positive displacement achieved should result in minimum job times and volumes pumped.

3. Both planning and operations are simplified by use only one density fluid completely filling the well. However, this overrides the possibility of minimizing surface and subsurface pressures required for control by using low density fluids as envisioned by Blount\textsuperscript{32}.

4. The dynamic seal – bullheading computer program can assist in off-bottom blowout control analysis and design. The many parameters that affect off-bottom blowout control design and the kill process can be investigated. These analyses can consider the effects of different kill fluid rate, density and viscosity, and injection string geometry and depth by changing the input data. This capability can be used to help determine the most appropriate kill approach for a given set of conditions, including the potential of achieving a kill with existing rig equipment.

5. The computer program was utilized to simulate the hydraulic conditions during the control of an actual underground blowout\textsuperscript{70} for the different pump rates and kill fluid densities utilized. The pressures predicted by the program have reasonably good agreement with the ones measured during the control. In addition, the individual dynamic seal and bullheading model predictions were also good when compared to published field case histories.

6. Likely applications for this method are similar to those for bullheading in general, but utilize the dynamic seal rather than a surface shut in. Nevertheless, the casing and/or formation strengths above the producing formation must be high enough to contain the pressure required to force the column of formation fluids back into an open formation, ideally the producing formation. If formation fluids are forced into fracture at a pressure that is inadequate to also force these fluids into the producing formation, an underground blowout may result.
7. A disadvantage of the proposed method is that the higher rates impose higher pressures on surface and downhole equipment and on the open formations. Therefore, the equipment used must have higher pressure ratings and the risk of lost returns, and possibly of underground blowout, is increased and must be considered explicitly.

8. When a blowout takes place, the magnitude of the blowout consequences can depend on the time to regain the control of the well. The selection of the intervention technique becomes a critical decision. Therefore, the optimum approach should be identified and implemented rapidly to lead to a successful blowout control operation on the first attempt and in the minimum amount of time.

### 6.3 Recommendations

The following recommendations are made for improving and validating the proposed new method.

1. Full-scale experiments to simulate the dynamic seal - bullheading process should be performed to demonstrate this method and help validate the models. This can be accomplished using the LSU#1 research well with some variation in well conditions and kill parameters.

2. Additional research needs to be carried out about the mathematical behavior of simultaneous upward and downward liquid flow since this is practically a new concept in blowout control and there is not a rigorous mathematical model to predict this phenomenon. It might be accomplished by performing a meticulous simultaneous solution among the injection string, annular section and the bullheading model, taking the injection depth as the solution point. The simultaneous upward and downward liquid flow is present after the dynamic seal is attained.

3. A fracture model should be added to the computer program to simulate how the fracture initiation and fracture propagation affects the pressure behavior during the control.
4. The possibility of including more than one permeable formation within the wellbore should be investigated as an improvement to the program. The same reservoir model can be utilized with different rock and formation fluid properties appropriate to each formation.

5. The dynamic seal model was applied to give a series of steady state solutions to involve the time in the process and obtain the required volume to reach the dynamic seal, however a more rigorous time–based simulation method such as a conventional finite difference approximation is recommended to model the dynamic seal process.

6. Experiments in the LSU’s 48-ft flow loop at different deviation angles should be conducted to establish a good basis for the development of a model of minimum velocity for effective bullheading for application to directional and high angle wells.

7. The mathematical models in the computer program should then be adapted to apply the proposed method in directional high angle well.
REFERENCES


8. Grace, Robert D., "Fluid dynamics kill Wyoming icicle" World Oil, April 1987


49. SPE Reprint Series No 42 "Well Control" 1996.


APPENDIX A

DERIVATION OF THE MOMENTUM KILL EQUATIONS

The mathematical model of Momentum kill is based on the Newton's second Law of Motion\textsuperscript{16}. Hence, the control volume formulation of Newton's second law, also know as the linear momentum equation is given by:

\[
M = \frac{\partial}{\partial t} \int v \rho dV + \int v \rho v \cdot dA \tag{A-1}
\]

Considering that the equilibrium condition has been reached after the well has been completely unloaded of all the mud and only formation fluid is flowing, the above equation becomes:

\[
M = \int v \rho v \cdot dA \tag{A-2}
\]

Developing the analysis for small intervals, a constant area for each interval can be considered. Therefore, Equation A-2 can be written as:

\[
M = v \rho v A \tag{A-3}
\]

In order to use English Engineering system of units, a constant of proportionality \((\gamma_c)\) must be included for the equation to be dimensionally homogeneous.

\[
M = \frac{v \rho v A}{\gamma_c} \tag{A-4}
\]
Substituting $q = vA$ in the Eq. A-4

$$M = \frac{v\rho q}{c} \quad (A-5)$$

On the other hand, the Mass conservation law, which states that the rate of increase of mass within the control volume plus the net rate at which mass flows out of the control volume is equal to zero, and is mathematically represented by:

$$0 = \frac{\partial}{\partial t} \int \rho dV + \int \rho v \cdot dA \quad (A-6)$$

Again considering that the equilibrium condition has been reached when only formation fluid is flowing, Eq. A-6 becomes:

$$0 = \int \rho v \cdot dA \quad (A-7)$$

Contemplating small length and constant area intervals, the above Equation would be:

$$0 = \rho v A \quad (A-8)$$

Equation A-8 can be also written as:

$$\rho v A = \rho_n v_n A \quad (A-9)$$

Solving the previous equation for velocity at the $n$ interval.
\begin{equation}
\rho_n = \frac{\rho g A}{\rho n A} = \frac{\rho g}{\rho_n A} \tag{A-10}
\end{equation}

The gas density at the \( n \) interval can be computed utilizing the real gas law, which is given by:

\begin{equation}
\rho_n = \frac{M_g p_n}{z_n RT_n} \tag{A-11}
\end{equation}

Where: \( M_g = \gamma_g M_a \)

Substituting the molecular weight of the gas \( (M_g) \) in Eq. A-11

\begin{equation}
\rho_n = \frac{\gamma_g M_a p_n}{z_n RT_n} \tag{A-12}
\end{equation}

Substituting Eq. A-12 in Eq. A-10

\begin{equation}
v_n = \frac{\rho g z_n RT_n}{\left( \frac{\gamma_g M_a p_n}{z_n RT_n} \right) A} = \frac{\rho g z_n RT_n}{\left( \gamma_g M_a p_n A \right)} \tag{A-13}
\end{equation}

Equation A-13 gives the formation fluid velocity at \( n \) conditions, and is the required one to calculate the momentum of the fluid given by Eq. A-5. Therefore, substituting Eq. A-13 in Eq. A-5.

\begin{equation}
M = \frac{\left( \frac{\rho g z_n RT_n}{\gamma_g M_a p_n A} \right) \rho g}{g_c} \tag{A-14}
\end{equation}
Simplifying the above equation

\[ M_u = \frac{P_{gsc}^2 q_{gsc}^2 z_n R T_n}{\gamma_s M_a p_n A g_c} \]  \hspace{1cm} (A-15)

Considering the following constant values:

\[ R = 10.73 \text{ psia} \cdot \text{ft}^3 \] \hspace{1cm} \text{lbm} \cdot \text{R} \\
\[ M_a = 28.966 \] \\
\[ g_c = 32.2 \text{ lbf} \cdot \text{ft} \] \hspace{1cm} \text{lbm} \cdot \text{sec}^2

\[ M_u = 0.0115 P_{gsc}^2 q_{gsc}^2 z_n T_n \] \hspace{1cm} (A-16)

Equation A-16 gives the momentum of the gas flowing up.

The momentum for the kill fluid is derived as follows. Taking Eq. A-5 and substituting \( v = \frac{q}{A} \) gives:

\[ M = \frac{q \rho q}{A g_c} \]  \hspace{1cm} (A-17)

Simplifying the above Equation.

\[ M_{ kf} = \frac{\rho_{ kf} q_{ kf}^2}{A g_c} \]  \hspace{1cm} (A-18)

In Equations A-16 and A-18, the area, \( A \), considered is that of the wellbore just below the injection point.

Solving Eq. A-18 for the control fluid flow rate.
Equation A-19 can be utilized to obtain the kill flow rate of a given fluid density to reach a required momentum. The required momentum must be at least that generated by the gas. Therefore, \( M_{kf} \) in Eq. A-19 would be substituted by \( M_g \) given by Equation A-16.
APPENDIX B

DERIVATION OF THE PRESSURE GRADIENT EQUATION

The pressure gradient equation is given by a combination of the Conservation of Momentum and Conservation of Mass. This appendix will show first the derivation of the conservation of momentum and then will combine the two conservation principles to obtain the pressure gradient equation.

The principle of Conservation of Momentum is derived from Newton’s second Law of Motion\textsuperscript{14}, which states that the net force acting on a system is equal to the rate of change of momentum of that system. Only forces acting at the boundaries of a prescribed space are concerned: any force within the space is involved only as one half of an "action - and - reaction" pair and so does not affect the overall behavior.

Mathematically, the Newton’s second law can be written as:

\[ \sum F = ma = m \frac{Dv}{Dt} = \frac{D(M)}{Dt} \quad (B-1) \]

The forces \( F \) acting in the boundary of a control volume that is inside of a circular pipe with upward flow are shown in Figure B-1.

The flow system is one-dimensional spatial geometry along wellbore and pipe due to the limited cross sectional size compared with the axial wellbore and pipe length.
Applying the Equation B-1 to a fluid flowing through the control volume yields the control volume formulation of Newton’s second law. It is also known as the linear momentum equation, which is given by:

\[ \sum F_{\text{external}} = \int_{cv} \rho \mathbf{v} \cdot dA + \frac{\partial}{\partial t} \int_{cv} \rho \mathbf{v} dV \]  \hspace{1cm} (B-2)

Where the external forces \( F_{\text{external}} \) are divided in surface forces and body forces.

\[ \sum F_S + \sum F_B = \int_{cv} \rho \mathbf{v} \cdot dA + \frac{\partial}{\partial t} \int_{cv} \rho \mathbf{v} dV \]  \hspace{1cm} (B-3)

Surface forces \( F_S \) are those that act on the boundaries of the system by virtue of their contact with the surroundings. Surface forces may be subdivided
into normal forces and tangential forces. Therefore, the above equation becomes:

\[ \sum F_p + \sum F_T + \sum F_B = \int_{cv} \nu p \cdot dA + \frac{\partial}{\partial t} \int_{cv} \nu p dV \]  \hspace{1cm} (B-4) 

Where:

\[ \int_{cv} \nu p \cdot dA \] = Flow rate of momentum (momentum flux through the control volume)

\[ \frac{\partial}{\partial t} \int_{cv} \nu p dV \] = Rate of change of momentum of the fluid in the control volume.

The components in the Equation B-4 are defined as follows:

**Normal Force** \((F_p)\):

Force due to the pressure into the system. It is given by:

\[ F_p = -\int_{cs} p \, dA \]  \hspace{1cm} (B-5) 

Where: \( p \) = Pressure at the interest depth.

\( A \) = Flow area.

The negative sign is introduced because pressure is a compressive stress acting in the inward direction on a surface and, for the surface element \( dA \) the positive normal acts in the outward direction.
**Tangential Force** \((F_T)\):

The tangent fluid force is due to the viscous shearing stress of the fluid. It is given by:

\[
F_T = \int \tau \, d\Lambda
\]  

(B-6)

Where:  
\(\tau\) = Shear stress.  
\(\Lambda\) = Contact area (surface of the pipe to oppose the flow, it can be through pipe, \(L \cdot \pi d\) or through annulus, \(L \cdot \pi d_c\)).

**Body Force** \((F_B)\):

The body force is due to the gravity force, which acts in the direction of the gravitational field. It is given by:

\[
F_B = g \int \rho \, dV
\]  

(B-7)

Where:  
\(g\) = Acceleration of gravity.  
\(\rho\) = Fluid density.  
\(V\) = Volume of fluid over the interest depth.

**Flow rate of momentum (momentum flux)** \(\int v \rho v \cdot dA\):

This term represents the flux or transport of momentum across the boundaries of the control surface.
Rate of change of momentum \( \left( \frac{\partial}{\partial t} \int \nu p dV \right) \):

This term represents the time rate of change of momentum of the fluid within the control volume. This term applies in unsteady flow conditions.

Substituting the acting forces (Equations B-5, B-6 and B-7) on the surface control into the Equation B-4.

\[
- \int_{c_s} p \, dA + \int_{c_s} \tau \, dA + g \int_{c_s} dV = \int_{c_s} \nu \rho v \cdot dA + \frac{\partial}{\partial t} \int_{c_s} \nu \rho \cdot dV
\]  

(B-8)

Equation B-8 is the linear momentum equation in an Integral control volume representation, which is widely used in problems related with fluid mechanics.

Another very common representation of the one-dimensional momentum equation is in differential form\(^{17,10}\), which all the terms are per unit volume. The flow rate of momentum (momentum flux) and the rate of change of momentum in differential form are derived as follows:

The second representation of the equation B-1 is given by:

\[
\sum F = m \frac{Dv}{Dt}
\]  

(B-9)

The derivative in the above equation is a derivative following a system of a fluid particle. Consequently, it is the substantial derivative\(^{38}\) (also called material derivative), and by definition in one dimension it is given by:

\[
\frac{Dv}{Dt} = v \frac{\partial (v)}{\partial L} + \frac{\partial (v)}{\partial t}
\]  

(B-10)
The first term of the right-hand side is called the convective acceleration, which arises when the particle moves through regions of varying velocity. The second one is called the local acceleration, which vanishes if the flow is steady (independent of time), in other words only an unsteady state can induce the local acceleration term. Substituting the above equation in the Newton's second law, and considering the terms per unit volume.

\[ \sum F = \rho \left( v \frac{\partial v}{\partial L} + \frac{\partial v}{\partial t} \right) \]  \hspace{1cm} (B-11)

Rearranging the previous equation becomes:

\[ \sum F = \frac{\partial (\rho v^2)}{\partial L} + \frac{\partial (\rho v)}{\partial t} \]  \hspace{1cm} (B-12)

Now the left-hand side components given on Eq. B-8 will also changed to differential form. The pressure term (normal force) in Eq. B-8 is changed to differential form using the divergence theorem of Gauss\(^{38}\), which states that surface integrals can be transformed into volume integrals. It is mathematically given by:

\[ \int_B \cdot dA = \int_B \text{divB} dV \]  \hspace{1cm} (B-13)

Where the divergence of the function \( B \) is represented by:

\[ \text{divB} = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} \]  \hspace{1cm} (B-14)

Therefore, applying the divergence theorem.
\[- \int_A (p) \cdot dA = - \int_V \text{div}(p) dV \]  \hspace{1cm} (B-15)

Hence, the one-dimensional pressure force term is given by:

\[- \int_V \frac{\partial p}{\partial L} dV = - \frac{\partial p}{\partial L} dL dA \]  \hspace{1cm} (B-16)

Finally, the pressure force term per unit volume will be

\[- \frac{\partial p}{\partial L} \]  \hspace{1cm} (B-17)

The other acting forces in the system (tangential force and body force respectively) given on Eq. B-8 for a constant cross sectional area are per unit volume given by:

\[ \int_{cs} \tau \, d\Lambda = \int_{cs} \tau \, (L \pi d) = \int_{cs} (\tau \pi d) dL \]  \hspace{1cm} (B-18)

\[ g \int_{cv} \rho \, dV = (\rho g) dAdL \]  \hspace{1cm} (B-19)

Hence, the total external forces per unit volume will be:

\[ \sum F_{\text{external}} = - \frac{\partial p}{\partial L} + \tau \frac{\pi d}{A} + \rho g \]  \hspace{1cm} (B-20)

Substituting the previous equation in Equation B-12, the conservation of linear momentum in differential form is mathematically represented by.
This form is more familiar to gas/oil well problems than the integral representation. Therefore, this scheme will be adopted in this work.

Evaluation of the wall shear stress ($\tau$) can be accomplished by using the dimensionless friction factor, which is defined as the ratio of the wall shear stress to the kinetic energy of the fluid per unit volume$^{34}$, thus.

$$f' = \frac{\tau}{\rho v^2 / 2}$$  \hspace{1cm} (B-22)

Where $f'$ is the Fanning friction factor. The Moody friction factor, $f$ (dimensionless), which is four times larger than the Fanning friction factor, is adopted in this analysis. Then, the shear stress ($\tau$) can be expressed as:

$$\tau = \frac{fpv^2}{8}$$  \hspace{1cm} (B-23)

Substituting the above formula and the area ($A = \pi d^2 / 4$) in Equation B-21 and rearranging yields

$$\frac{\partial}{\partial t} (\rho v) + \frac{\partial}{\partial L} (\rho v^2) = -\frac{\partial p}{\partial L} + \frac{fpv^2}{2d} + \rho g$$  \hspace{1cm} (B-24)

Hence, Equation B-24 is the unsteady state conservation of linear momentum. It is in consistent units.

On the other hand, the principle of Conservation of Mass simply states that the rate of increase of mass within the control volume plus the flux of mass across its control surface is zero. It is mathematically represented by:
\[
\frac{\partial}{\partial t} (\rho) + \frac{\partial}{\partial L} (\rho v) = 0 \tag{B-25}
\]

In steady state conditions the properties at every point in the system do not change with time, in other words, flow properties may vary from depth to depth in the system, but all properties remain constant with time at every place. Consequently, the time dependent term is zero. Thus, the one-dimensional momentum and mass balance equations become:

\[
\frac{d}{dL} (\rho v^2) = -\frac{dp}{dL} + \frac{f\rho v^2}{2d} + \rho g \tag{B-26}
\]

\[
\frac{d}{dL} (\rho v) = 0 \tag{B-27}
\]

Expanding the left-hand terms, in the above equations.

\[
v \left( \rho \frac{dv}{dL} + v \frac{dp}{dL} \right) + \rho v \frac{dv}{dL} = -\frac{dp}{dL} + \frac{f\rho v^2}{2d} + \rho g \tag{B-28}
\]

\[
\rho \frac{dv}{dL} + v \frac{dp}{dL} = 0 \tag{B-29}
\]

Combining the previous equations

\[
\rho v \frac{dv}{dL} = -\frac{dp}{dL} + \frac{f\rho v^2}{2d} + \rho g \tag{B-30}
\]

Solving Eq B-30 for the pressure gradient

\[
\frac{dp}{dL} = \frac{f\rho v^2}{2d} + \rho g + \rho v \frac{dv}{dL} \tag{B-31}
\]
Changing Equation B-31 to units utilized in this work

\[
\left( \frac{dp}{dL} \right)_t = \frac{fpv^2}{772.17d} + \frac{\rho}{144} + \frac{\rho \Delta v^2}{9273.6 \Delta L}
\]  \hspace{1cm} (B-32)

Equation B-32 is the pressure gradient equation, which is made up of three components.

\[
\left( \frac{dp}{dL} \right)_t = \left( \frac{dp}{dL} \right)_f + \left( \frac{dp}{dL} \right)_{el} + \left( \frac{dp}{dL} \right)_{acc}
\]  \hspace{1cm} (B-33)

The left-hand side component is the total pressure gradient. The first right hand side term accounts for frictional pressure losses due to the viscous shearing stress between the fluid and the wellbore/pipe wall and always causes a drop of pressure in direction of the flow. The second right hand side term accounts for the hydrostatic pressure of the fluid and acts in the direction of the gravitational field. The third right hand side component accounts for pressure changes caused by fluid acceleration, a pressure drop occurs in the direction that the velocity increases.
APPENDIX C

EXAMPLES OF THE OUTPUTS OF THE PROGRAM

Appendix C presents some examples of the outputs of the computer program for the hypothetical off-bottom blowout. It shows the results of the conventional dynamic kill for only one gas flow rate. It also presents the results during the bullheading process after the dynamic seal is reached as well as the bottomhole pressure, surface pressure, and gas flow rate as function of time during the complete control.
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<th>Section Length (ft)</th>
<th>Temperature (°F)</th>
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<th>Kill Fluid Data Flow Rate (BPM)</th>
<th>Pressure Profile (psia)</th>
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### Blowout Control using Dynamic Seal - Bullheading Concept

#### Bullheading Stage

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### Blowout Control Results

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VITA

Victor Gerardo Vallejo Arrieta, was born in Irapuato, Mexico. He received a Bachelor of Science degree in petroleum engineering from the Universidad Nacional Autonoma de Mexico in 1988.

In November 1988, he joined Petroleos Mexicanos, the National Oil Company of Mexico. He worked in drilling and completion operations in offshore platforms as well as well design at the Campeche Bay.

In August 1994, he entered Universidad Nacional Autonoma de Mexico, from which he received a master’s degree in petroleum engineering.

In November 1996, he returned to Campeche Bay, where he worked in well design.

In August 1998, he entered Louisiana State University to pursue the doctoral degree in petroleum engineering. Upon graduation, he will return to Mexico to work in Petroleos Mexicanos.