An approach for applying managed pressure drilling techniques to troublesome formations in an oil well in southern Iraq

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Abstract. Many southern Iraqi oil field formations, such as Dammam and Hartha, are characterised as loose formations, making overbalanced drilling difficult due to increased frequency and volume of mud losses. Managed pressure drilling techniques (MPD) may thus be applied. This process uses conventional hydrostatic column pressure and annular friction pressure in addition to the surface back pressure to generate a constant bottomhole pressure (CBHP) to drill such formations, which enables the use of the lowest mud weight (closest to pore pressure) and back pressure treatment utilising a choke manifold during the drilling process to maintain an equivalent circulating density (ECD) slightly greater than the pore pressure, reducing the risk of mud loss, and the concomitant stuck pipes and non-productive time (NPT), thus enhancing drilling efficiency. In this paper, Wellflo software was utilized to model multi-phase flow in wells to examine the use of aerated mud used at different injection rates for gas and liquid to identify the best injection rate for drilling operations without losses.

Several cases were examined using various mud weights and surface back pressure of the assumed injection rates, to choose the appropriate mud weight and the surface back pressure ranges. The highest pore pressure gradient expected in such holes is 0.465 psi/ft, and consequently, the minimum required mud weight was 8.95 ppg, in order to ensure control and avoid loss; however, due to back pressure and friction pressure in the annular region, this weight leads to problems in some formations. A mud weight of 8.8 ppg was therefore chosen as the closest feasible weight to pore pressure, with back pressures of 200 and 250 psi. A gas injection rate of 1,200 gpm was selected as the best injection rate for various liquid rates (581, 631, 681, 731, and 781 gpm). The use of aerated mud at 8.8 ppg mud weight increased the penetration rate, offering a more efficient cutting transportation ratio (CTR) and allowing more control over wellbore instability and formation damage, as well as limiting mud losses.

1. Introduction

Environmental conditions for drilling oil and gas wells are often difficult and hostile, and ongoing increases in demand for petroleum resources have exacerbated the oil and gas industry’s frequent issues with lost circulation. In the Basra oil fields, loss of circulation is a common problem that wastes time and money, with many negative aspects hampering the drilling process despite multiple efforts made to institute remedial practices to mitigate or avoid such problems. Such problems remain widespread and dangerous across the Basra oil fields [1], where lost circulation is expressed as total or partial loss of drilling fluid during penetration of formations in the drilling process, generally occurring when the openings of natural or induced formations are large enough to allow the passage of mud. When the hydrostatic pressure exceeds the pressure of the formation as influenced by conventional drilling fluids, mud losses represent a constant danger, especially in tanks with high permeability [2]. It is thus important for the industry identify and develop new technologies to improve drilling operations and to enable drillers to more accurately control pressures to reduce such drilling problems.

The managed pressure drilling (MPD) technique is an innovative method that allows better control of pressure changes during the drilling operation while using tools generally similar to those used in drilling underbalanced formations. The aim is to improve the drilling process by alleviating various
problems and thus improving costs by reducing non-productive time during which the drilling rig stops drilling [3]. The best option is generally considered to be constant bottomhole pressure during the application of MPD to the well, allowing more accurate wellbore pressure and the maintenance of slightly greater than pore pressure, which includes annular friction pressure and hydrostatic pressure in addition to surface back pressure [4].

Special techniques were used for calculating both the dynamic and static conditions in this paper, as the practical simulations were focused on the dynamic state seen during the circulation of the drilling fluid. The aim of this paper was to explain how to control the bottomhole pressure, restricting mud losses and the flow of the reservoir by using an MPD technique to improve the process of drilling a hole of 17.5 based on utilising the lowest possible mud weight to reduce the differential pressure between mud pressure and pore pressure, as well as using a two-phase drilling fluid with different gas/liquid ratios with applied surface back pressure.

1.1. Area of study
The Zubair oilfield is one of the largest oilfields globally and thus one of the most important fields in Iraq. The Zubair field is located in southern Iraq, 20 km southwest of the city of Basra. It was discovered by the Basra oil Company in 1949. The Zubair field is a cylindrical convex fold with a length of about 65 km and a width of 18 km. The southern part of the Zubair field extends into Kuwaiti territory, and the two main reservoirs are the Zubair formation and the Mishrif formation.

2. Overview
2.1. Drilling technologies
Under the supervision of Russian engineer, Semyonov, the first modern oil well was drilled in Baku in the 1840s. A decade later, the first oil well was drilled in the United States to a depth of 21m. Since then, drilling technology has developed extensively, with advanced technologies used presently including the use of a drilling fluid (mud) pumped through the drill pipe down to the bottom of the well through the bit. This exits through the annulus of the well, and the mud flows up, carrying cuttings out of the well. At the surface, the mud is separated from the return well flow, and stored in tanks (pits) before being pumped back down into the well to facilitate continuous drilling [5]. During the past century, oil and gas searches have gradually moved into more demanding environments that have required the development of new, safer techniques of drilling capable to handle complex situations. In general, the techniques of drilling commonly used now are

- Conventional drilling,
- Underbalanced drilling (UBD), and
- Managed Pressure drilling (MPD)

2.1.1. Managed Pressure Drilling (MPD)
Drilling operations are very expensive, and the oil and gas industry is constantly looking for new technologies to reduce costs and improve operations, particularly in overbalanced drilling situations which have pressure control issues, circulation loss, narrow pressure margins, differentially stuck pipe and significantly delays, which all create significant economic losses [6]. A few years ago, several studies determined that about 20 to 30% of the time spent in drilling operations was non-productive time (NPT), and that about half of this was related to wellbore pressure issues, as shown in figure 3. However, about 42% of this NPT, which includes problems related to wellbore pressure, can be minimised using MPD, one of the latest techniques of drilling. This is increasingly being used to drill wells which cannot utilise overbalanced drilling techniques [7]. According to the International Association Drilling Committee (IADC) definition of MPD, it is an adaptive drilling process used to more
precisely control the annular pressure profile throughout the wellbore, with the objective being to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile to match [8].

MPD techniques allow precise control of downhole pressure and are an acceptable solution in wellbore environments with narrow mud windows between the fracture pressure and pore pressure; if implemented successfully, they can therefore reduce downtime and costs considerably. This method attempts to manipulate downhole pressure in such a way that a longer hole section of the well can be drilled without fracturing the overlying formations in comparison with conventional drilling [9]. By examining the risks of drilling and drilling incidents affecting NPT in drilling operations, Malloy specified the problems related to NPT that can be mitigated by using MPD [10]:
- Lost Circulation,
- Wellbore Instability,
- Well Control and Influx Detection, and
- Stuck Pipes

2.1.2. Variations of MPD
Several variations of MPD have been developed recently, with the aim being more precise control of the annular pressure profile. Four variants are commonly used [12]:
- Constant Bottom-Hole Pressure (CBHP).
- Pressurized Mud-Cap Drilling (PMCD).
- Dual Gradient Drilling (DGD).
- Returns-Flow-Control (RFC).
This paper focuses on CBHP) drilling, however.

![Diagram of Closed MPD System]

**Figure 2.** The principle behind the closed MPD system [13].

### 2.1.3 Categorisation of Managed Pressure Drilling (MPD)

MPD may either be used as a primary mode during drilling operations or as a contingency plan. The IADC regulations for managed pressure thus classify MPD into two main categories, the proactive approach and the reactive approach.

1. **Reactive MPD:** The IADC defines reactive MPD as “Using MPD techniques and/or equipment just as a contingency to mitigate drilling problems as they arise” [14].

   In such cases, a well is designed to use conventional drilling techniques and MPD procedures and equipment are only activated where unplanned events occur. This means that, in the event of problems arising during conventional drilling, MPD techniques and equipment are available as a contingency. This approach thus does not harness all of the advantages provided by MPD [15]. Nevertheless, reactive MPD is common in onshore applications, as it allows operators to interact efficiently and safely, and the drilling rig must be equipped with at least a choke, RCD, and drill string non-return valves to facilitate this improved well control in order to handle any drilling surprises that occur during operation [16].

2. **Proactive MPD:** The IADC defines proactive MPD as “Using MPD techniques and/or equipment to precisely and actively control the pressure profile throughout the exposed wellbore” [14]. This approach thus utilises the wide range of techniques and tools available to develop preferential control, with fewer casing strings, better placement of casing seats, and better control of mud costs and mud density requirements. Using better pressure control also permits more advanced warning of potential incidents. These factors combine to reduce time spent in non-productive activities and to allow a better focus on the operations of drilling, allowing all MPD benefits to be exploited. In this category of MPD, the well is designed and planned for MPD techniques from initiation, allowing the operation...
to be equipped with all the tools required to accomplish efficient drilling and to manage the pressure profile of the wellbore [15]. In addition, according to Hannegen and Malloy [15], this is a beneficial and effective method for both onshore and offshore pressure profile control, as proactive MPD can provide active solutions for several major drilling problems, offering practical well drilling solutions that optimise drilling, and thus improving projects’ economy and operability.

3. Methodology

This section outlines the steps used to develop a hydraulic model to determine the feasibility and optimum parameters for various drilling operations that enables the identification of pressures, equivalent circulating density (ECD), cutting transport ratio (CTR) velocity, and other relevant hydraulic calculations. The highest pore pressure gradient expected in the type of hole intended is 0.465 psi/ft. Consequently, the minimum required mud weight to ensure primary control over the well is 8.95 ppg. However, at this mud weight, back pressure and annular frictional pressure may cause problems in some formations; thus, a mud weight less than 8.95 ppg was used during drilling to provide an adequate mud weight while controlling the formation pressure. To achieve this, aerated mud was used in the Wellflo program along with appropriate data for the well for the second hole in the study area, which includes six formations (Dammam, Rus, Umm-Er-Radhuma, Tayarat, Shiranish, and Hartha); however, the current work focuses on only two formations (Dammam and Hartha) in order to allow the development of an appropriate model.

3.1. Input data

Wellflo 8, Version 8.3.0 (1998) by Neotec, is a fluid hydraulics program capable of modeling multi-phase flow in wells. Although many other hydraulic programs exist in the industry, most are only appropriate for single-phase non-compressible flow.

When modelling using Wellflo to test the suitability of formation to be drilled using MPD, various input parameters such as depth for each formation, bottom hole assembly (BHA), pore and fracture pressure, as shown in table 1.

| No. | Parameter                              | Value                        |
|-----|----------------------------------------|------------------------------|
| 1   | Type of well                           | Vertical                     |
| 2   | Type of liquid                         | Water base mud (WBM)         |
| 3   | Type of gas                            | Nitrogen and Oxygen          |
| 4   | R300                                   | 42                           |
| 5   | R600                                   | 58                           |
| 6   | Water gravity                          | 8.33 ppg                     |
| 7   | Surface temperature                    | 80 F                         |
| 8   | Dimension of previous casing           | 18.625 OD (in)               |
|     |                                        | 17.689 ID (in)               |
| 9   | Previous hole size                     | 23 (in)                      |
| 10  | Borehole diameter                      | 17.5 (in)                    |
| 11  | Cutting size                           | 0.25 (in)                    |
| 12  | Pressure drop across BHA               | 500 (psi)                    |
| 13  | Motor pressure loss                    | 400 (psi)                    |
| 14  | Surface line friction pressure loss    | 50 (psi)                     |
3.2. The hydraulic model

In the required hydraulic model, several necessary conditions were considered:

1. Several mud weights were considered for drilling the section (8.7, 8.8, and 8.9 ppg); 8.8 ppg was selected as the best mud weight for drilling the section without adding problems.

2. More than one surface back pressure (SPB) was applied to each scenario to allow the selection of the most suitable pressure to keep the well under control, resulting in a 200 psi SBP being used for the Dammam and Rus formations and 250 psi SBP being used for the Umm-Er-Radhuma, Tayarat, Shiranish and Hartha formation.

3. For the aerated mud, the rates of gas injection inspected were 400, 800, 1,200, 1,600, and 2,000 gpm, with rates of liquid injection of 581, 631, 681, 731 and 781 gpm trialled to develop flow rates within the acceptable pressure windows for the different mud weights.

4. Results and discussion

To improve the drilling process of a 17.5 in hole section and to reduce drilling problems in such a section, MPD was considered, as this technique can increase the economic viability of drilling by avoiding various problems and thus reducing NPT, which reduces overall costs accordingly. The costs of drilling fluids were also reduced by using lighter liquids that significantly reduce mud losses. This task was performed in a manner that allows comparison with conventional drilling, with results offered for two scenarios [17]:

1. Drilling without SBP (Open hole conditions)
2. Drilling with SBP (Closed hole conditions)

A mud weight of 8.8 ppg was selected as the optimum weight to offer flexibility to deal with pressure changes while creating a suitable surface back pressure and reducing excess pressure against any formation that might affect flow. Increasing the back pressure causes increases in the pressure in the well, which can lead to the compression of gas inside the well, allowing more space for the liquid, and the rate of gas and liquid injection thus both play additional roles in this process. It was thus necessary to specify 50 psi surface back pressure applied in the first case for each formation in ongoing scenarios to accommodate friction losses. In the modelling this meant that the drilling process was first performed without using a chock, leaving it open to atmospheric pressure, while the second case was closed, with a chock was used, and thus when the 100 psi was applied, 50 psi pressure went to additional surface back pressure and 50 psi to accommodate friction losses. The pressure gradient, in addition to the ECD, was thus relied upon to choose the cases balanced or near-balanced with pore pressure, with red highlighting adopted to indicate underbalanced cases, and yellow used for balanced or near-balanced cases; green indicates cases of overbalance. All figures were drawn using Excel to graphically illustrate the relationship between the ECDs and the assumed gas/liquid injection rates.

4.1. At end of Dammam formation

The results for the site at the end of Dammam formation at 881 m without SBP at 50 psi and with SBP at 200 psi are offered below.

-Drilling without SBP (at 50 psi):

The results at the end of the Dammam formation at 881 m without SBP at 50 psi are shown in Table 2.
### Table 2. Results for 25 case of aerated mud at the end of the Dammam formation.

| Case | Water flow rate | Gas flow rate | BHP | ECD | CTR | P gradient | VL |
|------|----------------|---------------|-----|-----|-----|------------|----|
|      | Gpm            | Scfm          | Psi | Ppg | %   | Psi/ft     | Ft/h |
| 1    | 581            | 400           | 1255| 8.36| 0.8 | 0.435      | 52  |
| 2    | 581            | 800           | 1118| 7.44| 0.8 | 0.387      | 55  |
| 3    | 581            | 1200          | 991 | 6.60| 0.79| 0.343      | 59  |
| 4    | 581            | 1600          | 877 | 5.84| 0.79| 0.304      | 65  |
| 5    | 581            | 2000          | 775 | 5.16| 0.79| 0.268      | 73  |
| 6    | 631            | 400           | 1261| 8.40| 0.81| 0.437      | 56  |
| 7    | 631            | 800           | 1129| 7.52| 0.81| 0.391      | 59  |
| 8    | 631            | 1200          | 1008| 6.71| 0.8 | 0.349      | 64  |
| 9    | 631            | 1600          | 896 | 5.97| 0.8 | 0.310      | 69  |
| 10   | 631            | 2000          | 796 | 5.30| 0.79| 0.276      | 77  |
| 11   | 681            | 400           | 1266| 8.43| 0.81| 0.439      | 61  |
| 12   | 681            | 800           | 1140| 7.59| 0.81| 0.395      | 64  |
| 13   | 681            | 1200          | 1022| 6.81| 0.81| 0.354      | 68  |
| 14   | 681            | 1600          | 915 | 6.09| 0.81| 0.317      | 74  |
| 15   | 681            | 2000          | 817 | 5.44| 0.81| 0.283      | 81  |
| 16   | 731            | 400           | 1271| 8.47| 0.82| 0.440      | 65  |
| 17   | 731            | 800           | 1150| 7.66| 0.81| 0.398      | 68  |
| 18   | 731            | 1200          | 1037| 6.91| 0.81| 0.359      | 72  |
| 19   | 731            | 1600          | 932 | 6.21| 0.81| 0.323      | 78  |
| 20   | 731            | 2000          | 837 | 5.57| 0.81| 0.291      | 85  |
| 21   | 781            | 400           | 1276| 8.50| 0.82| 0.442      | 69  |
| 22   | 781            | 800           | 1159| 7.72| 0.82| 0.401      | 73  |
| 23   | 781            | 1200          | 1050| 6.99| 0.82| 0.364      | 77  |
| 24   | 781            | 1600          | 949 | 6.32| 0.82| 0.329      | 82  |
| 25   | 781            | 2000          | 855 | 5.7 | 0.82| 0.296      | 89  |
Figure 3. ECD vs gas injection rates for the end of the Dammam formation at 50 psi surface back pressure.

The results presented in table 2 were obtained by applying 50 psi SPB in a hole open to the atmosphere; the pore pressure at this point was 8.46 ppg, with a pressure gradient of 0.43 psi/ft. The formation was drilled in field using water-based mud with a weight of 9.1 ppg and a pressure gradient of 0.473 psi/ft; the balanced states or near-balanced states are thus those equal to or slightly greater than 0.43 psi/ft that are less than 0.47 psi/ft.

According to Table 2, significant differences arose between ECDs depending on the differences in the gas/liquid injection rates. ECDs were, in most cases, less than the pore pressure (under-balanced), with the exception of cases 16 to 21 which were balanced. The hole cleaning was generally good, however, as the cutting transport ratio (CTR) in all cases was greater than 0.5, ranging between 0.79 and 0.82. This type of mud is thus very effective at hole cleaning, with a high annular velocity and turbulent flow; as the rate of gas injection rate increased, the annular velocity increased, creating good hole cleaning and increased ROP. This is important, as improper hole cleaning leads to a decrease in ROP and this leads to problems such as stuck pipes; ROP must thus be taken into consideration when planning the drilling process.

For cases 16 and 21, the pressure gradients were 0.44 and 0.442 psi/ft, respectively; these were thus balanced with the pore pressure (8.46 ppg) and pressure gradient (0.43 psi/ft) by the increase in the injection rate of liquid versus gas. Both cases showed increased ECD and CTR in addition to a high annular velocity, though that in case 21 was higher than that in case 16; thus, the ROP was higher despite the slightly higher ECD in that case. Although UBD was better in terms of hole cleaning, higher ROP and minimisation of mud losses, the problem of fluid influx from the formation still occurred, in addition to wellbore instability, which is considered a significant problem. Figure 5 illustrates the changes in behaviour of ECD with changes in rates of gas and liquid injection, indicating an increase in ECD with an increase in the rate of liquid injection and a decrease with the gas rate, representing the
intersection of pore pressure with the liquid injection rate (731 and 781) gpm at the gas injection rate (400 scfm) seen in the mean states of the balanced cases, with pore pressure as shown in table 2. This offers possible combinations of injection rates in balanced cases, as well as clarifying the under balanced situations that drop below pore pressure.

- **Drilling with SBP (at 200 psi)**

The results at the end of the Dammam formation at 881 m with SBP at 200 psi are given in Table 3.

**Table 3.** Results of 25 case of aerated mud at the end of the Dammam formation.

| Case | Water flow rate | Gas flow rate | BHP | ECD | CTR | P gradient | VL |
|------|----------------|---------------|-----|-----|-----|------------|----|
|      | Gpm | Scfm | Psi | Ppg | %   | Psi/ft     | Ft/hr |
In this scenario, drilling with SBP at 200 psi led to a decrease in underbalanced cases and the emergence of more overbalanced cases, in addition to the presence of more balanced cases, as noted in Table 3 and Figure 6. The application of SBP at 200 psi gives the best results and offers an appropriate mixture of gas/liquid compared to SBP at 100 and 150 psi, where underbalanced situations occurred more frequently, thus increasing the risk of influx fluid from the formation and issues with wellbore instability. As noted in table 3, cases 3, 8, 13, 18, and 23, with pressure gradients 0.449, 0.452, 0.456, 0.459, and 0.463 psi/ft, respectively, are balanced with the pore pressure (8.46 ppg). The gas injection rate of 1200 scfm combined with the liquid injection rates of 581, 631, 681, 731, 781 gpm provided balanced situations, enabling effective drilling of the hole section while avoiding mud losses. In addition, good hole cleaning with CTRs ranging from 0.8 to 0.82 was observed, leading to increases in ROP over the overbalanced cases.

Gas injection rates higher than 1,200 scfm, (1,600 to 2,000 scfm) created underbalanced cases in which ECD was reduced and the annular velocity increased accordingly, thus increasing ROP, reducing losses and avoiding potential formation fracture; however, as mentioned above, the risk of influx fluid into the well remains.

For gas injection rates less than 1,200 scfm, many cases are overbalanced, and cases 1, 6, 11, 16, and 21, exceeded the ECDs applied in the field, risking formation fracture and mud losses, which may lead to stuck pipe problems, increasing NPT and drilling costs. Drilling with the application of SBP allows more control in ECDs as compared to drilling without SBP due to the ability to amend the gas/liquid ratio without stopping drilling as a result of pipe connection operations, which decreases CBHP as a result of the loss of the annular friction pressure. This pressure decrease leads to fluid flow from the formation or wellbore instability, machining it preferable to apply SBP, as dealing with mud losses
during drilling is preferable to dealing with well collapses that may stop the pipe as well as causing time losses.

Figure 6 show the relationship of ECD with the gas/liquid injection rate. The points of intersection of the pore pressure with the flow rate of the liquid represent the optimal mixtures of gas/liquid that provides balanced cases: the higher points represent the slightly balanced and overbalanced cases, while the points below the pore pressure represent the underbalanced cases.

4.2. At the end of the Hartha formation:
The results for the end of the Hartha formation at 1,887 m without SBP at 50 psi and with SBP at 250 psi are offered below.

- Drilling without SBP (at 50 psi):
The results at the end of the Hartha formation at 1,887 m without SBP (at 50 psi) are given in Table 4

Table 4. Results of 25 case of aerated mud at the end of the Hartha formation without SBP (50 psi).

| Case | Water flow rate Gpm | Gas flow rate Scfm | BHP psi | ECD Ppg | CTR % | P gradient Psi/ft | VL Ft/min |
|------|---------------------|--------------------|---------|---------|------|-----------------|----------|
| 1    | 581                 | 400                | 2761    | 8.59    | 0.79 | 0.446           | 52       |
| 2    | 581                 | 800                | 2588    | 8.05    | 0.79 | 0.418           | 53       |
| 3    | 581                 | 1200               | 2420    | 7.52    | 0.79 | 0.391           | 55       |
| 4    | 581                 | 1600               | 2257    | 7.02    | 0.79 | 0.365           | 56       |
| 5    | 581                 | 2000               | 2101    | 6.53    | 0.78 | 0.340           | 57       |
| 6    | 631                 | 400                | 2767    | 8.60    | 0.8  | 0.447           | 56       |
| 7    | 631                 | 800                | 2601    | 8.09    | 0.8  | 0.421           | 57       |
| 8    | 631                 | 1200               | 2441    | 7.59    | 0.79 | 0.395           | 59       |
| 9    | 631                 | 1600               | 2285    | 7.11    | 0.79 | 0.370           | 60       |
| 10   | 631                 | 2000               | 2135    | 6.64    | 0.79 | 0.345           | 62       |
| 11   | 681                 | 400                | 2772    | 8.62    | 0.8  | 0.448           | 60       |
| 12   | 681                 | 800                | 2614    | 8.13    | 0.8  | 0.423           | 62       |
| 13   | 681                 | 1200               | 2460    | 7.65    | 0.8  | 0.398           | 63       |
| 14   | 681                 | 1600               | 2311    | 7.19    | 0.8  | 0.374           | 65       |
| 15   | 681                 | 2000               | 2166    | 6.73    | 0.8  | 0.350           | 66       |
| 16   | 731                 | 400                | 2777    | 8.64    | 0.81 | 0.449           | 65       |
| 17   | 731                 | 800                | 2625    | 8.16    | 0.8  | 0.425           | 66       |
| 18   | 731                 | 1200               | 2478    | 7.71    | 0.8  | 0.401           | 67       |
| 19   | 731                 | 1600               | 2335    | 7.26    | 0.8  | 0.378           | 69       |
| 20   | 731                 | 2000               | 2196    | 6.83    | 0.8  | 0.355           | 71       |
| 21   | 781                 | 400                | 2781    | 8.65    | 0.81 | 0.450           | 69       |
| 22   | 781                 | 800                | 2636    | 8.20    | 0.81 | 0.426           | 70       |
| 23   | 781                 | 1200               | 2494    | 7.76    | 0.81 | 0.403           | 72       |
| 24   | 781                 | 1600               | 2357    | 7.33    | 0.81 | 0.381           | 73       |
| 25   | 781                 | 2000               | 2223    | 6.91    | 0.81 | 0.359           | 75       |
Table 4 and figure 7 show that the cases are generally in an underbalanced state, with no cases overbalanced or slightly balanced with the pore pressure at this point (8.95 ppg, with a pressure gradient of 0.465 psi/ft). The mud weight used in the field is 9.4 ppg, with a pressure gradient of 0.473 psi/ft, which is higher than ECD obtained from drilling without applied SBP (8.65 ppg, with a pressure gradient of 0.450 psi/ft) at 400 scfm and 781 gpm, with an annular velocity of 69 ft/min. Thus, good hole cleaning and increased ROP exist, though the risk of exposure to damage from even a slight blow or kick exists from Umm-Er-Radhuma and Tayarat to the top from Hartha. This impels control of the density of the mud, which also contains gaseous H₂S; the density of the mud should thus not be increased to avoid the occurrence of loss in the Hartha formation, and the liquid injection rate must be increased or surface back pressure added to control the well and reduce the costs resulting from the loss of flow operations, as well as the additional water rates required to increase ECD. Figure 7 shows that the operating window is below pore pressure here more significantly than in the rest of the formations due to the increases in depth and pore pressure.

**Figure 5.** ECD vs gas injection rate for each liquid rate for the end of the Hartha formation at 50 psi surface back pressure.
- **Drilling with SBP (250 psi)**:
The results at the end of the Hartha formation at 1887 m with SBP (250 psi).

**Table 5.** Results of 25 case of aerated mud at the end of the Hartha formation with SBP (250 psi).

| Case | Water flow rate | Gas flow rate | BHP | ECD | CTR | P gradient | VL  |
|------|----------------|---------------|-----|-----|-----|------------|-----|
|      | Gpm            | Scfm          | Psi | Ppg | %   | Psi/ft     | Ft/min |
| 1    | 581            | 400           | 3053| 9.49| 0.79| 0.494      | 51   |
| 2    | 581            | 800           | 2950| 9.17| 0.79| 0.477      | 53   |
| 3    | 581            | 1200          | 2846| 8.85| 0.79| 0.460      | 54   |
| 4    | 581            | 1600          | 2747| 8.54| 0.79| 0.444      | 55   |
| 5    | 581            | 2000          | 2653| 8.25| 0.78| 0.424      | 56   |
| 6    | 631            | 400           | 3056| 9.50| 0.8 | 0.494      | 56   |
| 7    | 631            | 800           | 2958| 9.20| 0.8 | 0.478      | 57   |
| 8    | 631            | 1200          | 2860| 8.89| 0.8 | 0.463      | 58   |
| 9    | 631            | 1600          | 2765| 8.60| 0.79| 0.447      | 59   |
| 10   | 631            | 2000          | 2674| 8.31| 0.79| 0.432      | 60   |
| 11   | 681            | 400           | 3058| 9.51| 0.8 | 0.494      | 60   |
| 12   | 681            | 800           | 2965| 9.22| 0.8 | 0.479      | 61   |
| 13   | 681            | 1200          | 2873| 8.93| 0.8 | 0.465      | 62   |
| 14   | 681            | 1600          | 2781| 8.65| 0.8 | 0.450      | 64   |
| 15   | 681            | 2000          | 2694| 8.38| 0.8 | 0.436      | 65   |
| 16   | 731            | 400           | 3060| 9.51| 0.81| 0.495      | 64   |
| 17   | 731            | 800           | 2972| 9.24| 0.81| 0.481      | 66   |
| 18   | 731            | 1200          | 2884| 8.97| 0.81| 0.466      | 67   |
| 19   | 731            | 1600          | 2797| 8.70| 0.81| 0.452      | 68   |
| 20   | 731            | 2000          | 2712| 8.43| 0.81| 0.439      | 69   |
| 21   | 781            | 400           | 3062| 9.52| 0.82| 0.495      | 69   |
| 22   | 781            | 800           | 2978| 9.26| 0.82| 0.482      | 70   |
| 23   | 781            | 1200          | 2894| 8.99| 0.81| 0.468      | 71   |
| 24   | 781            | 1600          | 2810| 8.741| 0.81 | 0.454     | 72   |
| 25   | 781            | 2000          | 2729| 8.49| 0.81| 0.441      | 74   |
Figure 6. ECD vs gas injection rate for each liquid rate for the end of the Hartha formation at 250 psi surface back pressure.

Despite the fact that drilling with applied SBP leads to an increased ECD compared to drilling without SBP, as a result of increased pore pressure and increased depth, most of the cases remain underbalanced, as shown in Table 5 and figure 8, though some cases become overbalanced. Only two cases are balanced or near-balanced with the pore pressure (8.95 ppg). As shown in table 5, case 18 with an ECD of 8.97 ppg and good hole cleaning with CTR 0.81, occurs with a pressure gradient of 0.466 psi/ft and an annular velocity of 67 ft/min, which generates an increase in ROP as compared to the cases OBD. The required water injection rate to achieve this is 731 gpm. In case 23, with ECD 8.99 ppg, pressure gradient 0.468 psi/ft, and CTR 0.81, an increase in the annular velocity to 71 ft/min is seen, which indicates an increase in ROP as compared with case 18. However, the rate of water injection for case 23 is 781 gpm, reducing the problem of loss in the Hartha formation by reducing the differential pressure between mud pressure and pore pressure. In general, influx control is difficult when drilling without SBP or even in, most cases when implementing SBP although reducing the problem of mud losses by keeping CBHP less than the pore pressure ensures that the cleaning of the well is good. Cases 18 and 23 can be used to drill in Hartha to increase the possibility of avoiding mud loss in addition and to avoid flow into Tayarat and Umm-Er-Radhuma by reducing the mud weight to avoid losses in the Hartha.
formation. The presence of the choke reduces the problems in controlling the well. Figure 8 clarifies that the conditions for underbalanced are decreased as compared to those in figure 7, with the operating window giving the best mixture of gas/liquid injection rates to balance with pore pressure at the intersection of the pore pressure and injection rates.

5. Conclusions

1- The study used simulations to show that the MPD technique provides a way to drill hole sections of 17.5 inches for different pore pressures in an economical, efficient and safe manner.

2- The use of the MPD technique reduces NPT, thus reducing the cost of the process as well as allowing more accurate management of the properties of the mud to preserve CBHP in the etched section; this is based on the flexibility obtained from adding a choke and implementing SBP.

3- Drilling with applied SBP using aerated mud allows more control over the well based on controlling BHP and ECD.

4- Drilling by adding SBP allows an increase in the control of the flow of fluids from the formation, as well as reducing the problem of instability in the wellbore as compared to drilling without SBP; however, it also reduces ROP and increases mud losses. In addition, the higher the SBP, the lower the annular velocity.

5- BHP and ECD increase as the depth increases, while SBP decreases as the gas injection rate increases.

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